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EXPLORATION FOR FOSSIL AND NUCLEAR FUELS FROM ORBITAL ALTITUDES

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NOVEMBER 1974

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ABSTRACT

Studies of ERTS-1 and Skylab-EREP data have defined both the advantages and limitations of space platforms as a new "tool" in mineral exploration. Generally, useful information can be extracted from synoptic imagery and/or the direct measurements of surface reflectances from which small-scale reconnaissance geologic maps are produced, previous maps are edited and refined, landform types are better evaluated in context, and structural deformations and fracture trends are determined on a regional basis. Information about rock composition, stratigraphic ages, and "telltale" chemical alterations as guides to subsurface deposits are less reliable.

Remote sensing data from satellites are being applied to hydrocarbon exploration by many oil companies, although very few have reported "open file" results to date. One ERTS investigation in the Anadarko Basin of Oklahoma has demonstrated a remarkably high correlation between several types of anomalies recognized in the imagery and the locations of known oil and gas fields. These exceptional surface features include: 1) surface expression of underlying structures, 2) circular drainage patterns, 3) linear controls (faults and fractures), 4) tonal anomalies (nature unknown), and 5) "Hazy" anomalies (chemical alteration; geobotanical anomalies; man's activities?). When used during the exploration phase, ERTS data serve to localize areas for more intensive study by field mapping, geophysical and geochemical methods, and subsurface drilling. By reducing large areas to prime "targets" of maximum likelihood, the ERTS overview approach should save a considerable fraction of the exploration costs, and in some instances should assist significantly in making new discoveries.

In addition to supporting several ERTS follow-on investigations in petroleum exploration, NASA has approved a broad in-house study at Goddard Space Flight Center designed to verify the general applicability of the initial Anadarko Basin results. Using both conventional photogeologic methods and special computer processing, imagery taken over such oil-producing provinces as the Williston Basin, North Dakota, the Green River and Wind River Basins of Wyoming, the Denver-Julesburg Basin, several west Texas fields, and Gulf Coast salt domes is being subjected to detailed analysis in search of definitive recognition criteria.

Goddard is also engaged in a smaller-scoped study of ore guides, such as "iron stain" surface alteration and delineation of fracture traces, associated with the sedimentary "roll" deposits of uranium minerals in Wyoming.

INTRODUCTION

A pressing need to find new methods and approaches in exploring for oil and gas and other sources of fuels no longer requires demonstration or proof. Any American who experienced interminable waits in long gas lines in the 1973 winter of discontent, or reacts to his ever-rising monthly utility bill, or simply reads the depressing reports of still-impending energy crises in his local newspaper will not require any convincing to become alarmed about the outlook for the future. Many responses to these problems have been advanced—conservation, pressures on our foreign supplies, and accelerated development of solar, aeolian, geothermal, and fusion energy sources lead the list.

An acceleration in exploration is another obvious response. Tried and true techniques will be applied with increased vigor. But, innovative and even unconventional techniques must also be devised, tested, and put into operation as soon as they are declared to be practical and productive.

One such novel technique has moved across the horizon of possibility and looms now as one of the more promising approaches in an expanding search for fuel sources and other raw materials relevant to a rising worldwide demand for more energy. The approach is simply to use orbital space platforms—both automated satellites and manned space vehicles—from which to gain a new perspective of the Earth's surface by means of standard and/or specialized remote sensing techniques. This approach is actually an outgrowth of many years of aerial photography as applied to geologic mapping and mineral exploration. Its important new (although not unique) advantages over the commonly used conventional aerial systems are:

(1) the greatly expanded synoptic view provided by individual images owing to a ten to hundredfold increase in operating altitudes coupled with high resolution imaging sensors,

(2) the high frequency of (repetitive) coverage resulting from the numerous orbital passes available during spacecraft missions of months (manned) to years (satellites) duration,

(3) the use of a variety of sensors extending through several regions of the electromagnetic spectrum, including multispectral imagers, that acquire coherent data simultaneously, and

(4) the ease with which orbital remote sensing data can be transmitted or later converted into a digital mode, allowing their further treatment by a wide range of computer-processing techniques involving enhancements, selective information extraction, comparison of repetitive scenes, etc. to be made on a large volume of information.

Practical remote sensing from space platforms began almost with the launch of the first rockets that carried recoverable photographic equipment. Photographic data recording wide areas of the Earth's surface continued to be gathered on nearly all manned missions from Mercury and Gemini through Apollo. Weather satellite systems, such as TIROS and Nimbus, returned useful data on the land and sea surfaces in addition to the atmospheric data for which they are designed. Drawing upon years of experience in remote sensing from aircraft, the designers of orbital remote sensing platforms placed the first "sophisticated" multispectral sensor system on ERTS-1, the Earth Resources Technology Satellite launched in mid-1972. Soon thereafter the Skylab manned laboratory began to acquire an even broader range of remotely-sensed data, using film cameras, multispectral scanners, an infrared spectrometer, and several radiometers. Future systems now on the "drawing boards" will incorporate this growing wealth of experience with a new generation of varied sensors in space. Thus will emerge ever more versatile research satellites and, in all likelihood, on-line or operational satellites (such as the EOS series) and spacelabs (including shuttle-serviced stations).

In keeping with the author's current base of experience, this paper will confine its topics almost exclusively to results from the ERTS program pertinent to exploration for oil and gas and, more briefly, for uranium deposits. The remainder of the paper is divided into four parts: 1) a review of achievements to date in relevant aspects of general geologic studies from ERTS, 2) a survey of reported accomplishments oriented specifically towards exploration for energy sources (with emphasis on petroleum), 3) an evaluation of the prospects and limitations of the space platform approach to fuel exploration, and 4) an examination of continuing programs now funded or planned that are designed to "prove out" the use of ERTS and other space systems in exploring for fuel resources.

Before proceeding through these four sections, it is appropriate to summarize as a "preview" the present status of exploration for fossil and nuclear fuels from space. Simply synopsized, it must be stated that, as far as NASA officials can determine, no previously unknown petroleum or uranium deposits have yet been discovered directly (and probably indirectly) from interpretation of images or other forms of remotely-sensed data obtained either from satellites or from visual and/or instrument observations made by astronauts. However, "rumors" have reached the author and others of considerable interest in this approach by oil companies and other exploration-minded enterprises. It is in the nature of the petroleum industry to be secretive about successes with new techniques that score in finding oil and gas – witness the delay of several years in making seismic prospecting generally available throughout the industry after a few companies had verified its value. What has been brought to light by ERTS in particular which provides invaluable adjunct or supplementary data to the exploration scientists are these accomplishments: 1) updating and refining rock unit boundaries and distributions on small-scale maps, 2) recognition of hitherto unsuspected lineations – especially regional straight to circular or arcuate fracture systems – that could control or influence the location of oil traps or uranium concentrations, 3) better definition of often subtly expressed geomorphic "anomalies" that bear some relation to subsurface structures, and 4) an apparent surface manifestation of alterations of rock, soil, or vegetation tied to escaping hydrocarbons or to redistribution of elements associated with shallow uranium deposits. According to the growing convictions of those geologists now working with NASA's Earth Resources programs, it is just a matter of time before an oil field or a nuclear ore deposit is found through the use of significant data obtained from ERTS or some other spaceborne sensing system as an integral part of the exploration program.

PART 1: PROGRAM RESULTS*

A. General View: The ERTS-1 spacecraft was launched on July 23, 1972 from NASA's Western Test Facility in California. Both the Return Beam Vidicon (RBV) and the Multispectral Scanner (MSS) began to transmit image data on July 26, 1972. Owing to a switching circuit problem, the RBV has been shut down since early August of 1972. As of October 1, 1974, the MSS has imaged more than 100,000 scenes covering greater than 85% of the Earth's land surface. About 30%, on average, of these scenes are largely cloud-free and well-illuminated. Coverage of all of North America has been continuous but coverage of other continents became severely limited by tape recorder difficulties since March 1973.

The reader is urged to consult the three volume Proceedings of the Second (March 5-9, 1973) and Third (December 10-14, 1973) Symposia on Significant Results from the Earth Resources Technology Satellite** for detailed treatment by the investigators, program managers, agency

*Most of Part 1 has been extracted from the NASA-Goddard Space Flight Center X- Document X-650-73-316 entitled Earth Observations from Space: Outlook for the Geologic Sciences, by Nicholas M. Short and Paul D. Lowman, Jr., October, 1973.

**Volume I of each Symposium Proceedings is available from the Government Printing Office; inquiries about availability of Volumes II and III can be made there.

representatives, and invited speakers of the major findings of ERTS-1 for the various discipline groups comprising the Earth Resources program.

B. Value of Synoptic Coverage: ERTS provides a remarkable sequence of uniformly illuminated, essentially planimetric vertical views of the Earth's surface that cover very large areas (~12,500 square miles) in an image obtained from the 570 mile orbital altitude. Like the Gemini-Apollo pictures, these images are invaluable because of their synoptic aspects—that is, a single scene (approximately 115 miles on a side) surveys a wide variety of terrain, geology, and land use types under near-optimum viewing conditions that emphasize the contextual relations of these surface features. Unlike the Gemini and Apollo pictures, or those from Skylab, the ERTS images meet the necessary conditions for being readily joined together in mosaics. This greatly increases the synoptic character of this imagery and extends the assessment of contextual relationships to regional and even subcontinental proportions. The resulting mosaics are surprisingly close to being orthographic, as can be determined by comparing both individual images and composite mosaics to such projections as Albers Equal Area or Lambert Conformal.

ERTS-1 has now acquired enough cloud-free imagery to allow assembly of vast areas of Earth in mosaics. Some spectacular examples have already been made public. A black and white (red band 5) mosaic of the entire state of Oregon is reproduced here (Figure 1) and many other states individually as well as the entire continental United States have been similarly mosaicked. Color mosaics are completed for the eastern United States from Maine to Florida, the entire western coastal United States, Florida, Louisiana, Michigan, Wyoming, and Montana (among others), and for several regional sections. Foreign areas available in color now include Italy, parts of west Africa, all of Iran, the Red Sea area, and Yemen.

Beyond the esthetic and technical achievements associated with such mosaics, the scientific merts alone—particularly in geology—are a sufficient justification for their production. Comparison of small-scale geologic or physiographic maps of large areas with ERTS mosaics reveals at once the remarkable utility of the latter for presenting regional interrelationships among major structural or land-form units. Such mosaics are especially suited to lineaments analysis where uniform lighting serves to highlight trends of continuous, often deep-seated fracture zones.

C. Other Special Advantages of ERTS: Geologists experienced in using radar imagery look forward to the day when an active microwave system is flown on a spacecraft. One property of radar, that of cloud penetration, offers a distinct advantage in regions which are habitually overcast. Another important property, at least of some of the microwave bands now used, is the "apparent penetration" of heavy foliage which allows radar to "see" the terrain beneath an extensive tree canopy. It is surprising to note that under some conditions, the images made from the ERTS infrared (IR) channels (Bands 6 and 7) will provide a rendition that has a "quasi-radar" aspect. This is graphically displayed in Figure 2 where the thick jungle in southern Venezuela appears almost uniformly black in the green and red bands (4 and 5) but seemingly is "stripped" to bare ground in the IR bands. In reality, the close association of canopy profile with ground topography is being revealed when the foliage is examined in the highly reflective infrared. The crystalline rock terrain can be broadly defined and differentiated in the IR band image.

Some stereo capability exists for ERTS images where sufficient sidelap is maintained. However, most of each scene cannot be viewed in this way. Using the multispectral scanner data stored on the digital tapes, members of the U.S. Geological Survey remote sensing facility at Flagstaff, Arizona have developed a reprocessing procedure that produces a pseudo-relief or "3-D" effect. One phase of that procedure involves a change in the contrast ratios of grey levels in a given band—this selective darkening and lightening acts much like air-brush shading used to give an appearance of relief to a topographic sketch map of mountainous terrain. An example of the final product is shown in Figure 3.

D. Specific Geologic Applications: It should be kept in mind that ERTS is basically an extension of aerial photography to large area mapping. Aerial photographs in the past have been used chiefly as aids to the geologist in preparing or revising various kinds of geologic maps. The techniques and approaches of photo-interpretation developed prior to availability of multispectral imagery from space remain the major tools by which geologists extract information from ERTS data. Because of the decrease in resolution (by factors ranging from 5 to 100), certain types of information found in aerial photos are inherently unrecoverable from ERTS but such deficiencies are offset by the synoptic overviews that provide hitherto unobtainable information. Thus, some tasks will still be done better from aircraft but others may be done best—and even exclusively—from space platforms.

One measure of success of ERTS in geology is the extent to which new information has been acquired. While it is still premature to assign a dollar value or cost-effectiveness rating to the results reported so far, it is clear that significant benefits are gradually accruing from ERTS data to the specific applications outlined in Table 1. In time, accomplishments in each of these fields will be translated into economic payoffs as new mineral deposits and oil prospects are discovered and engineering projects are undertaken because of these scientific and technological advances flowing from ERTS and other programs that couple space-acquired data with conventional ground exploration methods. The outlook is especially promising for certain parts of the world where ERTS images represent the first detailed surface coverage of regions never before surveyed or mapped beyond a reconnaissance level.

Some of these applications are reviewed in the following sections:

(1) Map Editing: To some extent, ERTS data can be used to make new maps but these would not be equivalent to those produced from aerial photographs. In order to construct a standard geologic map, it is normally necessary to recognize stratigraphic units and sequences at the formation or even member level and, to a lesser extent, to discriminate among the major lithologies in the area. For mapping from aerial photos, this requires recognition of unit boundaries and definition of differences among units on the basis of rock color and/or surface weathering effects, topographic and/or geomorphic expression, soil associations, and characteristic vegetative cover, among other criteria. Most units depicted on large-scale maps range in thickness from a few tens to a few hundred feet at most. However, because of resolution limitations, most stratigraphic units (defined from ground studies by criteria that usually require close-up or even hand specimen examination) cannot be recognized and separated in ERTS images along the same boundaries selected for mapping purposes. Several ground-distinguishable units with similar reflectance properties (termed remote sensing units) might group or blend into a single discernible unit in an ERTS image that may or may not have a meaningful stratigraphic and/or lithologic significance. When examined in the field, some remote sensing units actually correspond to single stratigraphic units but others are comprised of several stratigraphic units having similar reflectance.

Nevertheless, under suitable conditions geologic maps of considerable usefulness have already been produced from ERTS imagery. The example from Wyoming shown in Figure 4, when compared with the published map of the same area, indicates that new units having a field-checked reality were defined from the ERTS images even though the contacts among these or previously known units may not be as precisely located as those in the ground-based map version. In some instances mapping from ERTS can be made more accurate by referral to coverage from several

Table 1

Applications of ERTS to Geology

Map Editing:
• Boundary and Contact Location
• Stratigraphic and/or "Remote Sensing" Unit Discrimination
• Scale-change Corrections
• Computer-processed "Materials" Units Maps
Landforms Analysis:
• Regional or Synoptic Classification and Mapping
• Thematic Geomorphology (e.g., Desert, Glacial, Volcanic Terrains)
Structural Geology:
• Synoptic Overviews of Tectonic Elements
• Appraisal of Structural Styles
• Lineaments (and "Linears") Detection and Mapping
• Metamorphic and Instrusion Patterns
• Recognition of Circular Features
Lithologic Identification:
• Color-Brightness (Spectral Reflectance) Classification
• Ratio Techniques
• Photogeologic Approach
Mineral-Exploration:
• Reconnaissance Geologic Mapping
• Lineaments Trends (especially Intersections)
• Surface Coloration ("Blooms" and "Gossans")
• Band Ratio Color Renditions
Engineering and Environmental Geology:
• Dynamic Geologic Processes (Sedimentation and Coastal Processes; Sea Ice; Active Glaciers; Permaforst Effects; Landslides and Mass Wasting; Shifting Sand Seas; Land Erosion)
• Strip Mining; Surface Fractures – Mine Safety
• Construction Materials

seasons, as effectively illustrated in Figure 5. This makes use of the repetitive (18-day cycle) aspect of ERTS coverage from its near-polar orbit.

A more immediate application of ERTS images lies in map editing or revising of previous small-scale maps. In regions of the world where rock exposures are sharply defined (mainly in deserts or other areas of low vegetation), the correspondence of ERTS-viewed surface geology patterns with those in the maps is almost self-evident (Figure 6a and b). But, close comparison of image to map frequently points to serious discrepancies in the map version. Reality resides with the ERTS image.

(2) Lithologic Identification: Identification of rock types from aerial or space platforms has long been a goal that consistently remains elusive. The high hopes that at least the major rock groups could be recognized with presently used remote sensor data have met with varied success. Depending on the experience of the interpreter and his awareness of the rock types known to occur in the imaged area, the photogeologist frequently has been able to correctly identify basalts, granitic rocks, some metamorphic types, limestones, shales, and sandstones. This ability will, of course, decrease considerably as resolution becomes too poor to single out individual lithologic units. However, in some geologic terrains, generally homogeneous rock units are exposed over wide enough surfaces to produce distinguishing tones and patterns in ERTS imagery, as illustrated in Figure 7.

It is not likely that remote sensors operating from space will ever achieve a high degree of reliability in rock type identification. Unlike laboratory methods, such as x-ray diffraction in which unique solutions to component mineral identity result from fundamentally different combinations of atomic structure, there is little that most remote sensing devices can measure that is exclusive to any given rock type. In the spectral range scanned by the ERTS MSS, the only rock properties directly measured are color and brightness; indirectly, derivative properties such as relative erodability (expressed topographically), surface stains, soil associations, structural response, vegetation preferences, etc. are taken into account in making identifications. However, it is not possible to set up a meaningful working classification of rocks based primarily on typical colors and relative brightness (most classifications are built from mineral assemblages, textural aspects, and field relationships). Thus, granites and schists, sandstones and limestones, shales and slates, and other lithologically or genetically dissimilar rock pairings may have roughly the same colors and brightnesses. Conversely, one given rock type may have many color variants as, for example, green, red, buff, gray, and black shales, or white, dark-gray, buff, and red limestones.

(3) Structural Geology: Experience with earlier space imagery had disclosed the exceptional value of synoptic imagery for displaying extended structural elements such as closed anticlines, domes, and intrusive bodies, folded mountain belts, fault zones, regional joint patterns, and other fracture systems in their regional context. In arid regions, especially, the surface expression of structurally disturbed parts of the crust was often better revealed in the images than in maps of the same areas. The interplay among underlying structure, topography, vegetational distributions, and solar illumination commonly enhanced the appearance of structural elements, so that subtle relationships not apparent on the maps were made to stand out. New lineaments of considerable magnitude and extent were picked out in the images because their breadth and continuity were commonly overlooked on the ground where only small, localized effects of a segment exposed discontinuously from one outcrop or topographic expression to the next were insufficient to manifest the "whole from the parts". In some areas of the world (e.g., Gulf of Oman; the Afar; Afghanistan) space imagery has brought about improved understanding or even fundamental resynthesis of the tectonic framework. ERTS has broadened these observations to sections of the globe never before imaged in detail from space. Four outstanding ERTS views of complexly folded and faulted parts of the crust are documented in Figure 8 a-d.

As expected, the principal output so far from examination of ERTS images for new structural information is the recognition of numerous linear features, ranging in length from 1-2 miles up to several hundred miles. Almost every ERTS image having notable geologic content is marked also by occasional to frequent linears. In the first rush to report significant results, investigators usually equated these linears with structural features such as faults, joints, or inclined strata. Many of these interpretations have stood the test of field-checking. But others have been abandoned when individual linears were found to be lighting artifacts, spurious alignments of diverse ground features, or man-made objects; the degree to which a region is vegetated represents another factor that influences the apparent occurrence of linears.

The geologic studies of the state of New York by Y. W. Isachsen provide a case in point. At the March 1973 ERTS Symposium, Isachsen displayed a mosaic of the state which has been analyzed for structural features. His efforts concentrated on the Adirondack and Catskill Mountains (Figure 9) where large crustal fractures were well-known and mapped, in part because of their control on regional topography. He has since presented an updated ERTS-based map (Figure 10) of linears of all kinds observed in the eastern half of New York. His first appraisal of these linears had indicated 1) many of those already recorded from geologic studies were recognizable, 2) while other known ones which should be visible did not show up, and 3) still others prominent in ERTS images were completely new features not recorded on any maps. However, after careful field-checking and examination of maps and photos, he concluded that less than 1/3 of the new linears are likely to be strictly structural in nature. Many undiscerned faults and lineaments fail to be expressed in ERTS images because of unfavorable illuminations and/or degradation effects in the 3rd- and 4th-generation images used.

Another study reported by N. H. Fisher and his colleagues in the Australian ERTS investigations is particularly instructive. Several test areas that have been thoroughly studied and mapped over the years on the ground and from aerial photographs were chosen for comparison with the information content extractable from ERTS. In the case of linears, it was found that only 30% and 10% of the previously known faults and major fractures were recognized in the 1:1,000,000 and 1:250,000 scale ERTS images respectively covering the same area. Furthermore, many of the ERTS-identified linears were new and did not coincide with the field-mapped lineaments. Also, radar-detected lineament patterns generally were not compatible with the ERTS linear sets. This discrepancy between ERTS and ground truth, while it seemingly casts doubt on the validity and reliability of the space imagery as a discriminator of structural features tends to be reduced when it was realized that the mapped lineaments 1) were often defined by criteria discernible only on the ground (e.g., fault gouge, slickensides), 2) included many short lineaments below the maximum length (1-2 miles) detectable from ERTS imagery, 3) often consisted of close-spaced sets counted as single linears in ERTS scenes, and 4) did not suffer from the bias of one-time-a-day coverage at mid-morning. A related Australian study disclosed an additional effect of operator bias: the same interpreter picked out (or missed) different linears when examing the same image at intervals several months apart and several interpreters tended to produce different, subjective linears maps from the same image.

The Wind River Mountains of Wyoming provide a dramatic indication of the rapidity with which a mapping effort can be accomplished using ERTS imagery. Dr. R. Parker of the University of Wyoming has been mapping in the high country of this range for five years—a task carried out on pack mule and "shanks-mare" in the grand tradition. His labors led to the map produced in Figure 11 left. After receipt of ERTS imagery covering this range, he completed the map shown in Figure 11 right in just 3 hours. Although this map should be rated as "preliminary" because most of the lineaments have not been verified, some confidence in the correctness of identification is afforded by field checks at several localities where evidence of fracturing was then obtained. Still, a note of caution has been added to this work following receipt of some Skylab imagery of the same area. A linears map made from the Skylab scene is compared with the ERTS version in Figure 12. The difference in numbers of linears detected results from the higher resolution of the Skylab metric camera. The differences in orientation of prevailing linears is almost certainly due to the times of day when the data were acquired—the morning sun direction from ERTS favors enhancement of northeast sets while the afternoon sun-illuminated images from Skylab emphasize north to northwest sets.

ERTS has shown a special – almost unique – facility for calling attention to circular as well as linear features. Most of these are volcanic or intrusive in nature and many are newly recognized. The circular or arcuate markings traced in Figure 13 are thought to be fractures in the country rocks overlying a series of intrusives in central Colorado. Similar curved linear features, consisting of segments that commonly encompass a full 360° are in places associated with porphyry copper deposits in many parts of the world. Again, these may have developed over stocks and diapirs but many are believed to be fractures within the initial subsurface or "roots" zone of volcanoes long since eroded below their cones or craters.

ERTS mosaics are ideal for getting a perspective on the tectonic framework of large regions of the crust (Figure 14). Thus, through-going lineaments that continue for hundreds of miles can be integrated into a unified network which reflects the influence of fractures in an ancient basement or results from stress systems developed from more recent plate tectonic movements. Seen in a broad context, where diversities of topography and surface geology tend to be filtered out, a new synthesis of structural data can emerge. Various investigators are even now building revised structural models from ERTS for their regions of interest. Some first results of one such effort applied to all of the conterminous United States are depicted in Figure 15, although no follow-up verification of the existence of heretofore unrecognized lineaments has been carried out as yet.

(4) <u>Mineral Exploration</u>: Work to date has pinpointed two potentially useful ways in which ERTS data could help to locate conditions favorable to the concentration of metals and other mineral materials. First, the recognition of new crustal fractures and, especially, intersections in lineaments systems improves the probability of finding ore <u>if</u> one believes in the commonly held view that such fractures control localization of mineralizing solutions. Each new fracture or intersection provides new targets for exploration. Point intersections, particularly, represent a significant narrowing in on promising zones of concentration so that exploration of vast areas can be greatly compressed. An example of this approach has already been presented in Figure 12.

Second, many shallow mineral deposits give rise to distinctive surface stains (gossans and blooms) caused by alteration or secondary enrichment. If broad enough, some of these stains should be detectable as color-brightness anomalies—subject to the caveats raised in the section on lithologic identification. A simple test of this capability would be to look at ERTS imagery for any evident visual (tonal) differences around known mineral deposits that single them out from their surroundings. Caution must be maintained in examining active mining areas to avoid confusion between surface conditions at man-made workings (excavations; mine dumps; dried-up lakes, etc.) and natural stains present before exploitation.

A. F. H. Goetz (Jet Propulsion Lab) and L. C. Rowan (U.S. Geological Survey) have developed a computer-based method for enhancing ERTS imagery to bring out the effects of surface alteration; usually subtle accumulations of hydrated iron oxide (iron rust or gossan) associated with sulphide deposits are emphasized. From field and laboratory measurements with a reflectance spectrometer, these investigators have confirmed that limonite has a spectral response quite unlike that of most other common minerals. This response can be made more sensitive to small difference when several ratios of different ERTS MSS band pairs are calculated. Each resulting ratio represents a variable signal which, like individual MSS band analog signals, can be used to construct photo images. The individual ratio images are passed through an optical processor using color filters to produce a color composite. Filter combinations have been found that cause the tones or grey levels representing limonite in three different ratio images to appear a yellowish-brown much like that of iron stain. Different rock types, vegetation, etc. also take on distinctive hues; in particular, clay alteration products also indicative of certain ore deposits can be made to take on a characteristic set of colors. Goetz and Rowan have tried out their method on an ERTS scene of central Nevada that includes the Goldfield mining district (gold and silver accompanied by iron sulphide). Prominent yellow-brown color patterns are observed around Goldfield (principally in a ring or aureole that roughly outlines that alteration zone surrounding the underlying intrusive) and other areas where surface iron stains were known before. The color composite has now been field-checked from the air and ground during which many of these color anomalies were verified. Insofar as gossan often indicates mineralization (including uranium ores), this enhancement technique, if it bears up under further testing, may well prove to be a major breakthrough in mineral prospecting.

PART 2: SPECIFIC RESULTS IN FUELS EXPLORATION

Both direct and indirect information bearing on the search for gas and oil and for uranium can be gleaned from ERTS data. Some types of direct information are obvious to anyone familiar with the use of aerial photographs in geologic exploration. Most have been alluded to in Part 1, along with certain reservations in their accuracy and utility. Among those guides to presence of underground fuel sources recognizable at the surface are: 1) lithologic units (reservoir rocks or host beds) whose subsurface extensions elsewhere can be inferred, 2) folded structures that persist at depth, 3) relatively short lineations and fracture or joint sets that may localize mineralization or trap petroleum below, and 4) generally longer regional linear systems that afford clues to basement trends responsible for controlling structural and/or stratigraphic traps. Previous illustrations provide examples of the ability of ERTS to detect and define such features. Another relevant example appears in Figure 16 which shows how readily ERTS can pick out some of the classic salt domes in the Gulf Coast from which petroleum products have been recovered.

Still another example is that of the actual presence of oil at the surface. This is a rare condition on the land (tar sands and pits being the exception) but natural seeps on the seafloor give rise to surface slicks analogous to the better publicized oil spills. Geologists at the Conoco Oil Company Research Laboratory in Ponca City, Oklahoma, working with the NASA aircraft facility at Johnson Spacecraft Center in Houston, have demonstrated the detectability of marine natural seeps as these are manifested on the ocean surface. Images obtained through narrow band blue filters on photographic cameras during aircraft flights over known seeps in the Gulf of Mexico readily display the outlines of the surface collection of oil (Figure 17) but film exposed to longer wavelengths fails to define the same spots.

As examples of diverse indirect information types, one can cite 1) possible effects of petroleum on vegetation—a contemporaneous phenomenon, and 2) recognition of modern-day sediment distribution patterns (Figure 18) in coastal, estaurine, or lacustrine waters, from which comes new insight into the accumulation of source beds or reservoir units in depositional basins of the geologic past.

Of the 72 ERTS-1 NASA-approved investigations in geology, perhaps more than half provided useful information of immediate interest to a petroleum geologist looking for principles or demonstrations of the exploration capabilities of space imagery. Some of the same information is applicable to the geologist searching for uranium. A few of the investigations dealt specifically with suggested applications to fuels exploration as a secondary concern or by-product of their main objectives. Only one investigation was completely dedicated to the use of ERTS data for petroleum exploration while no investigation considered the question of prospecting for uranium from space.

The sole ERTS investigation in petroleum exploration was conducted by R. J. Collins, Jr., president of the Eason Oil Company of Oklahoma City, and his colleagues. Under his direction, the field and interpretive work was carried out by F. P. McCown, L. P. Stonis, and G. J. Petzel of the company and J. R. Everett of the Earth Satellite Corporation, Washington, D.C.

Their philosophy underlying the objectives of the study followed a sound and proper approach: Concentrate on a major oil basin already in production as though it were an unknown or virgin territory earmarked for the first phases of exploration. This outlook tends to reduce the bias of familiarity but still retains the eventual opportunity to compare their findings with established ground truth, namely, the location of productive fields and the data on the geologic factors responsible for the petroleum accumulations.

The choice of test area was dictated in part by company interests and proximity but was also based on a set of conditions that offered an optimum appraisal of the potentialities of exploration from space. Thus, the Anadarko Basin of southwest Oklahoma and the Texas Panhandle was selected for detailed analysis. This is one of the older oil-producing regions in the United States—having been developed in the 1920s. More than 25 major producing fields occur in the structural traps within the basin and many more are found in stratigraphic traps.

The basin consists of a west-northwest-trending subsidence trough that was filled with more than 45,000 feet of epicontinental sedimentary rocks from the early Cambrian through the Pennsylvanian. Maximum sedimentation took place in the Pennsylvanian when about 11,000 feet of clastic rocks were deposited. Subsequent to this the basin underwent strong deformation, more or less contemporaneous with that in the Ouachita Basin further east, leading to a steepening of the southern basin flank accompanied by extensive basement faulting that carried crystalline rocks upward at the Wichita Mountains. Following rapid erosion, about 3000 feet of Permian red beds, saline deposits, and carbonates were laid unconformably over the now asymmetric basin—these units are only slightly deformed. Thin deposits of Tertiary sediments cover the western part of the basin.

The modern-day surface, therefore, consists of flat-lying Permian and younger sedimentary rocks which show little or no direct evidence of the subsurface conditions around the structural traps (except for several fields along the south limb). Most traps lie below 2000 feet but many occur at depths of 8000-12000 feet, and, more recently, production has reached 17000 feet and deeper. The present surface is used both for farming (wheat, etc.) and ranching. Scattered woods mixed with shortgrass are interspersed with farmlands on the eastern side. This gradually gives way westward to country used primarily for grazing in open rolling long grass prairie and sagebrush. The test area, then, is characterized as a low to high plains on which several different vegetation covers have developed on soils derived from near-surface rocks that have no involvement with the more deeply buried and "masked" producing zones. This type of petroleum environment provides an exacting test of the capability of ERTS to "sense" clues to hidden petroleum reserves.

The Eason Oil investigators have compiled one of the most comprehensive and analytical reports in the geology phase of the ERTS program. They have thoroughly documented the variety of techniques used in their study. They have demonstrated the degree of reliability to which small-scale mapping can be done from space imagery and have shown the value of multi-seasonal coverage in separating and identifying surface units. They have also evaluated the presumptive cost-effectiveness of the ERTS approach to petroleum exploration—major savings in the initial (or reconnaissance) stages of exploration are indicated and further savings are suggested for later stages, as for example a potential reduction in the number of seismic lines that may otherwise have been planned which could then be eliminated over areas rated as unfavorable for accumulation. However, in the remainder of this survey of their results, we shall confine our attention to the two most promising observations that could lead directly to the discovery of petroleum.

First, as did most other investigations, the Eason Oil group gathered a great deal of new information on surface linears. This is almost self-evident in comparing Figures 19a and b. The increase in known linears as defined in ERTS images is impressive, so much so that it raises a question of doubt in any petroleum geologist (by nature a skeptic made so through the experience of many dry holes) as to their validity. The immediate reaction is to wonder why only a few of the linears have been found in the field or through subsurface drilling. One obvious answer is that they have—but the policy of propietary use practiced by the oil companies has prevented the linears from being recorded on published maps. However, the investigators discount this as a prime explanation. Another answer resides in the definition of linears—many may be non-geological and only a fraction might be fracture zones, faults, or surface expressions of basement lineations. The investigators again counter this by claiming that almost everywhere they field-checked roadcuts along the linears path they found some verification of a recorded linear even though that same linear was usually "invisible" in aerial photos or by visual inspection from an aircraft. The question remains open but, suffice to say, the likelihood that many of the linears actually exist as structural features seems reasonably high in the Anadarko Basin. The importance of this in oil-finding is that 1) more oil traps can now be looked for, 2) the linears themselves—if they are fracture zones—can be loci of increased porosity, especially at intersections, and 3) the patterns revealed by the linears should better define regional stress fields and trends of structural adjustment.

The second important result concerns several types of surface anomalies defined by the investigators. A few individual examples can be seen in the ERTS image reproduced in Figure 20, although most are revealed only by inspection of transparencies on a light table. Most of these anomaly types have been categorized as closed anomalies, in that they can be circumscribed by a boundary line. One type clearly is due to drainage patterns, some of which represent adjustments to subsurface structures, such as an anticline over which younger strata have unevenly settled. Another type is topographic, caused in some instances by differential erosion. Still another comes under the heading of geomorphic and is based on subjective interpretations by the investigators. Less definitive, but nevertheless recognizable in the imagery are the two classes termed tonal and textural anomalies. Tonal anomalies are expressed as unaccounted-for differences in grey level whereas textural anomalies appear as streaked, mottled, or rough patterns in the imagery. These may have a variety of causes, from cultural activities, or as peculiarities in soil, rock, or vegetation cover, through geological effects of uncertain nature, to unusual reflectances of unexplained origin. Figure 24 presents a map of the large or more conspicuous closed anomalies over the Anadarko Basin. Many of these, however, show no positive correlation with, or superposition on, underlying oil and gas fields.

Two classes of anomalies yield a high correlation with the location of producing areas. One is the geomorphic-topographic type. The other is the so-called hazy anomalies (see Figure 20)—described by the investigators as resembling a "blurring" or "smudging" of the photo-image. A map of their distribution in the basin appears in Figure 22. The extent to which both classes correlate with known fields is outlined in Table 2 along with data on the other anomaly types. Some of the hazy anomalies occur over fields producing from structural traps as much as 8000-14000 feet down; anomalies over stratigraphic traps are rare. The correlation is so strong that one must accept some kind of relationship between a surface effect and the presence of petroleum beneath, even though the nature of that relationship is not yet settled and is still open to suspicion.

Table 2

Closed Anomalies

Survey 1 (Fall)	Geomorphic, Tonal & "Hazy" Anomalies	
76	Total Anomalies	
59	Producing Fields	
11	Nonproductive Structures	
6	No Coincidence	
33 of 37	Geomorphic	Anomalies coincide with field or Structure
33 of 35	"Hazy"	
0 of 4	Tonal	
Survey 2 (Fall and Spring)	**"Hazy" Anomalies**	
57	Total Anomalies	
42	Producing Fields	
6	Nonproductive Structures	
9	No Coincidence	

The investigators note that the hazy anomalies are best seen in dry weather fall images and are also well displayed in west spring imagery. They are best developed in grazing lands on the west but are less easily found in farmlands. Almost invariably, when visited on the ground, they coincide with local areas of sandy soils that, in places, even have formed into dune-like deposits. They also tend to associate with the Ogallala formation or in Plio-Pleistocene terrace deposits.

Already these hazy features have engendered considerable debate as to their nature, cause, and value as a guide to petroleum. Two diverse views will be discussed here—the opinion of the present author is intertwined with those of other supporters or critics.

One piece of evidence is given as a computer-processed enlargement (Figure 23) of the ERTS view of the most prominent hazy anomaly shown in Figure 20, that in the bend of the Canadian River near Webb, Oklahoma. This rendition is remarkably similar in details to the view presented in an RB-57 high altitude aerial photo. Both show extensive drilling and pumping sites along a network of roads. Ground inspection indicates the presence of stabilized sand dunes and very sandy soils. An hypothesis to explain this–and other hazy anomalies elsewhere–simply holds them to be consequence of man's activities in extracting the oil, such as damage to the terrain by countless vehicles and bulldozers plus possible effects from escaping hydrocarbons, that may have occurred prior to current land use and restoration regulations. However, the explanation does not adequately account for the extensive sand deposits unless it is assumed that so much vegetation has been stripped off that the area(s) converted to a sand waste during the dust bowl days (or at a later time).

A competing explanation is more exciting and desirable to those seeking to show the utility of orbital exploration. This postulates that hydrocarbons have leaked or migrated up and out from the trap and upon reaching the surficial layers introduce chemical and/or botanical changes. This idea is old–the notion of telltale alterations by escaping gases or fluids has long been advocated despite meager proof. One variant holds to geochemical changes in bedrock or soil resulting in bleaching or staining to produce color anomalies. Another envisions the escaping substances as reacting with the country rock to induce distinctive metasomatic products. A third considers the hydrocarbons as capable of moderating surface vegetation–either by killing off plant life and therefore accelerating erosion or by "fertilizing" the soil and thereby stabilizing growth. This last view might seem to apply to the sand-rich hazy anomalies, if toxic hydrocarbons have damaged the grasses and sage, allowing an increase in loss of the fine fractions from the soils or if beneficial hydrocarbons have fostered thicker vegetation that causes the sand to pile up.

So far, no decisive data have been gathered to explain the specific nature of these anomalies. However, T. J. Donovan of the U.S. Geological Survey reports in the March, 1974 issue of the American Association of Petroleum Geology Bulletin (v. 58, pp. 429-446) the results of some highly relevant analyses at the Cement field near the axis of the Anadarko Basin. This field occurs within a long doubly plunging anticline which, unlike most in this basin, has prominent surface expression. Exposed bedrock consists of Permian red sandstones and gypsum beds. In the field in many places, the sandstone has been bleached to a yellowish-brown to white color (Figure 24). This is ascribed to the reducing action of hydrocarbons carried in expelled reservoir pore waters. The gypsum beds are converted to low porosity carbonate rocks. Sandstones are also re-cemented by migrating carbonate solutions. Both the metasomatized gypsum and these sandstones tend to form more resistant rocks that stand above the terrain as butte-like outliers.

Such effects have been observed before but their relationship to hydrocarbons has never been firmly established. However, Donovan has determined the carbon and oxygen isotope compositions (Figure 25a and b) of the Permian sandstone and has been able to explain the extremely anomalous isotopic compositions–a deficiency of C^{13} and exceptionally high O^{18}–by a plausible geochemical model dependent on the reducing action of CH_4 and other hydrocarbons. He has also found anomalies at six other localities overlying producing fields.

Strangely, the Cement field itself is detected only with difficulty in the ERTS imagery. This is unexpected in view of the prominent color and rock type changes noted at the surface. Special enhancement techniques (e.g., those developed by Goetz and Rowan) may be needed to discriminate these surface alterations in some kinds of terrain or surface materials. However, Donovan's results look highly promising as a general guide to petroleum accumulation if it is ultimately proved that 1) reservoirs leak, 2) the escaping products reach the surface, 3) these products interact with surface materials to bring about discernible changes, and 4) the changes are detectable from space.

In closing Part 2, I shall state briefly that some of the observations made at the Anadarko Basin, together with the results of Goetz and Rowan discussed in Part 1, have a direct bearing on prospecting for certain kinds of ore deposits. Like most mineral deposits, uranium ores tend to be localized by fractures—hence any new information on linears will be helpful in exploration. One type of uranium deposit—the sedimentary roll deposits of Wyoming and Colorado are excellent examples—in most instances is accompanied by secondary hydrated iron oxides released from the original source rocks or the eventual host rocks in the migrating solutions that concentrate the ore. This gossan is commonly located at the surface over the roll front. Present exploration methods include a search for iron staining of soils or surficial bedrock and in some instances the limonite alteration products are widespread enough to be detectable from aircraft (and by presumption from space). The band ratio method that worked in the Goldfield, Nevada district has not yet been tried on an area of known uranium roll deposits but it is reasonable to expect some success in its use.

PART 3: EVALUATION OF THE POTENTIAL FOR PETROLEUM EXPLORATION FROM SPACE

Too little work has been done to date to allow a definitive prediction about the outlook or prospects for success of petroleum prospecting from satellites or other orbiting platforms. However, enough has been learned already from the ERTS investigations in geology, and particularly those carried out by Eason Oil Company and by Goetz and Rowan to permit a summary to be made of the positive factors which offer real promise for the approach. These are:

(1) Improved perspective of exposed surface structural expressions.

(2) Subtle indications of subsurface structures through drainage control (circular or offset stream patterns) and other geomorphic anomalies.

(3) Direct indications of linears or circular features that can be related to local to regional fractures and lineations which also influence the localization of petroleum.

(4) Recognition of distinctive tonal or hazy anomalies, especially through enhancement techniques, that are eventually proved to be caused by or related to natural petroleum occurrences.

(5) Association of geobotanical anomalies with the subsurface presence of petroleum; this has not yet been established.

Enough experience is at hand to suggest a suitable working procedure for the analysis of ERTS imagery in search of guides or clues to petroleum. The procedure should begin with a standard photogeologic interpretation of ERTS transparencies and paper prints leading to maps of surface materials units, linears, and various types of closed anomalies. This should be accompanied by preparation of appropriate color composites. Special processing should follow: this should include edge enhancements (by optical, electronic, or computer techniques) to bring out more information on linears and band ratioing (with color output) and other computer-based data reformating methods.

At this point it is wise to reiterate emphatically that remote sensing from aircraft and/or spacecraft is not a "magic black box" method that will supercede the many tried and true field and instrumental methods used over the years in petroleum exploration. Remote sensing is still just another "tool" in the workbox of skilled, intuitive exploration geologists. It will be put to its best use when it is considered as another data source to be integrated with field mapping, subsurface data, and methods that can detect geophysical, geochemical, and geobotanical anomalies.

A word of caution about the limitations already set forth by doubting critics (which include from time to time even some of us who are actively trying to apply remote sensing to petroleum exploration). Among these are:

(1) Surface indications of oil and gas are relatively uncommon and most have probably already been detected in the more accessible parts of the world.

(2) Today, most new oil discoveries are being made primarily through use of geophysical methods and by drilling inasmuch as the most decisive data now needed relates to deeply buried subsurface conditions that generally have poor surface expression.

(3) The precise role of linears in localizing oil has not been fully established; depends on time of formation, depth to producing zone(s), caprocks characteristics, etc.

(4) Geological complexities (unconformities, glacial cover, etc.) unrelated to petroleum accumulation frequently mask oil and gas traps.

(5) The hypothesis that hydrocarbons can escape to the surface and cause recognizable alteration effects is unproved; the rate of escape may be less than the rate of surface erosion or other removal factors.

(6) It is difficult to assess man's role or that of vegetation in producing (or obscuring) tonal and hazy anomalies.

PART 4: CURRENT PROGRAMS TO TEST THE REMOTE SENSING APPROACH

The results of the Eason Oil study have been sufficiently encouraging to prompt NASA to continue and expand its efforts to evaluate the feasibility of exploring for petroleum (and, to a limited extent, uranium) from ERTS and Skylab data already on hand and from satellites or manned missions planned for the future. The philosophy behind this decision is this:

(1) As part of the mandate in its Earth Resources program, NASA has an obligation to demonstrate the value of remote sensing from aircraft and space-platforms and to make the resulting information public.

(2) At this time, at least, NASA must do this "proofing" as the oil companies are likely to be reticent in revealing their own conclusions.

(3) For a start, it is important that the Anadarko results previous reported be thoroughly checked and understood.

(4) Positive, or at the minimum encouraging, results should be obtained from no less than 5 other petroleum provinces or basins, preferably from a variety of surface terrains, before it is

reasonable to argue for general acceptance of orbital remote sensing as a valuable adjunct to petroleum exploration.

In line with this philosophy, the NASA Office of Applications is presently supporting the following studies: 1) An ERTS-1 Follow-on Investigation for further studies at the Anadarko Basin and then the Powder River Basin, to be carried out by T. J. Donovan and L. Rowan of the U.S. Geological Survey in cooperation with A. F. H. Goetz of the Jet Propulsion Laboratory; this study will utilize both the geochemical approach developed by Donovan and the image enhancement techniques applied by Goetz and Rowan to sulphide ore deposits; 2) A series of studies (as described in the next paragraph) to be conducted by the Geology Group of the Earth Resources Branch at Goddard Space Flight Center. In addition, assistance in the above two studies is being considered by NASA's newly-formed Office of Energy Programs, under the direction of Dr. H. H. (Jack) Schmitt, as one of its priority activities. Finally, encouragement has been given to the author, in his role as coordinator of Geology investigations in the Earth Resources program, to set up liason and develop a strong working arrangement with the exploration geologists and other professionals in the oil industry and petroleum institutes.

The investigation program in petroleum exploration at Goddard Space Flight Center has now been defined and will essentially follow this approach:

(1) Familiarization with criteria used by Eason Oil-Earth Satellite Corp. in the Anadarko Basin study.

(2) Modification and adjustment of these criteria in light of new information and techniques.

(3) Development of optical and computer techniques at Goddard comparable to those now being used by Goetz at the Jet Propulsion Laboratory; development of new techniques as needed.

(4) Work with the U.S. Geological Survey in a coordinated effort.

(5) Completion of a "pilot" study by "re-doing" the Anadarko Basin as a control.

(6) Application of the methods and skills to several new fields; candidates include a) West Texas-Midland, b) Denver-Julesburg Basin, c) Wind River and/or Green River, Wyoming, d) Bakersfield, Calif., e) East Texas, f) Illinois Basin; g) Williston Basin.

(7) A tie-in of results with data from other exploration methods.

(8) Development of a model or working procedure for petroleum exploration.

SUMMARY STATEMENT

Evaluation of investigation results from ERTS-1 leads to the conclusion that this satellite can do many of the same prime tasks in geological applications done in the past four decades with aerial photography. A broad challenge has been thrust upon geologists to more fully exploit and extend these accomplishments. The ever-rising demands for more energy sources and related raw materials places petroleum exploration near the top of the list of priority applications of space-acquired data that must still be demonstrated and implemented.

Figure 1. Uncontrolled photomosaic made from ERTS images acquired in 1972 showing the entire state of Oregon and parts of the surrounding states of California, Idaho, and Washington. All images were produced from red band 5 (courtesy Oregon State University).

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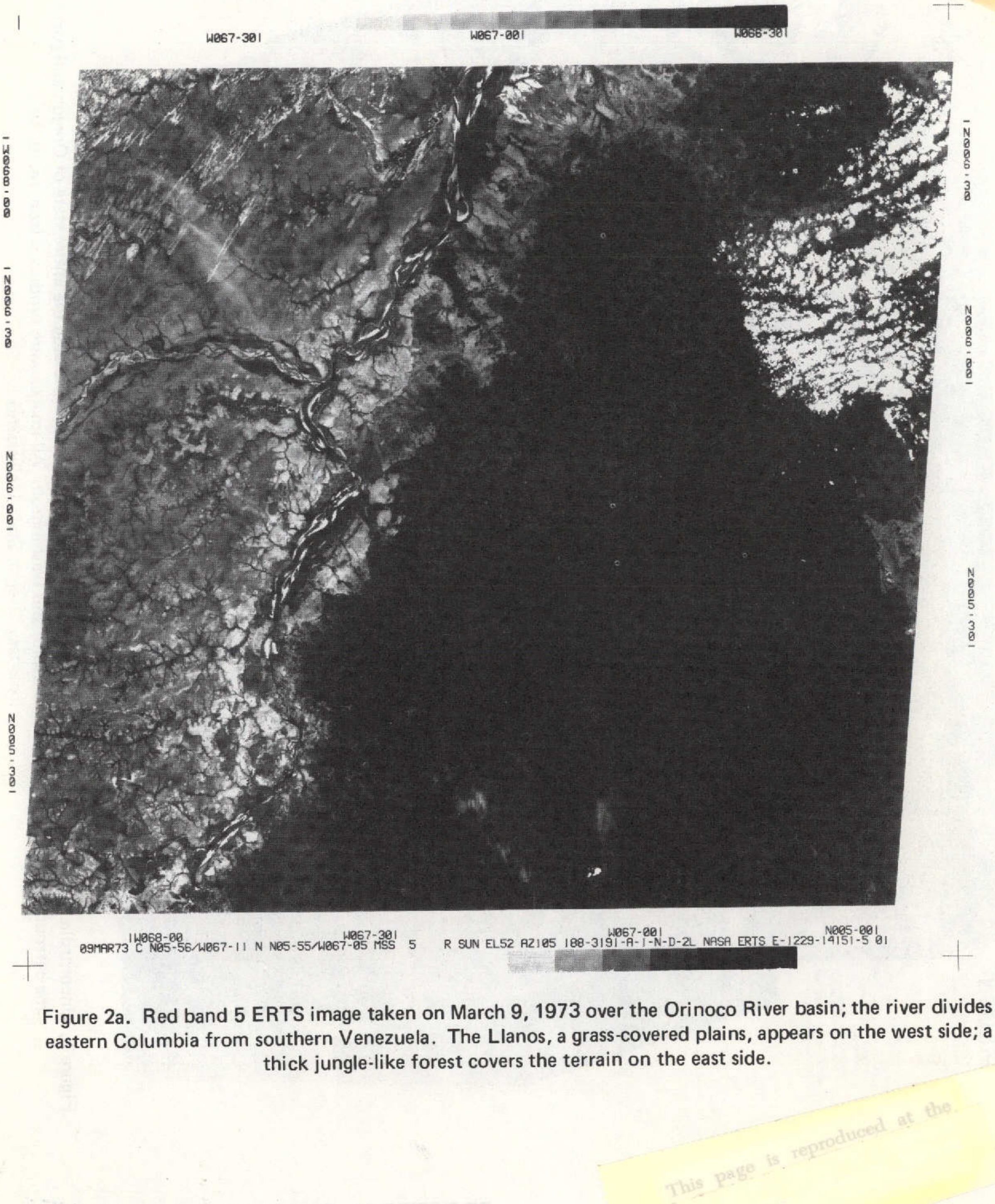

Figure 2a. Red band 5 ERTS image taken on March 9, 1973 over the Orinoco River basin; the river divides eastern Columbia from southern Venezuela. The Llanos, a grass-covered plains, appears on the west side; a thick jungle-like forest covers the terrain on the east side.

Figure 2b. IR band 7 ERTS image of the same scene shown on the opposite page. Some of the details in the Llanos are emphasized by the stronger contrast. The dark jungle cover seen in the band 5 image now acts as though it has been "penetrated", revealing the underlying terrain, here consisting of Precambrian igneous and metamorphic rocks.

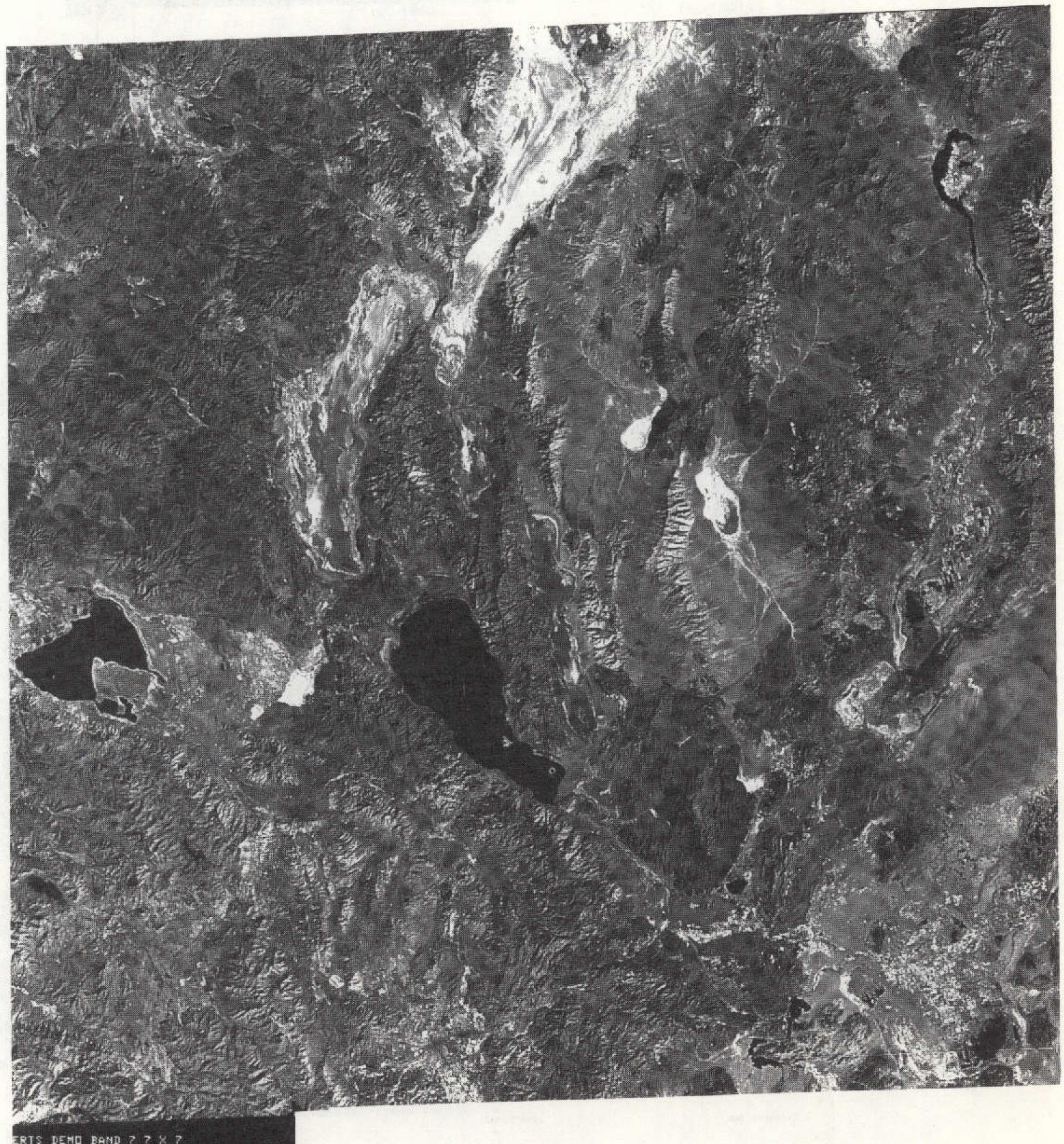

Figure 3. Computer-reprocessed rendition of the band 7 ERTS image taken on November 22, 1973 by the multispectral scanner as the spacecraft passed over western Nevada (Reno in lower left; Pyramid Lake in center; Black Rock desert at top). The pseudo-relief effect is the result of contrast stretching (courtesy U.S. Geological Survey).

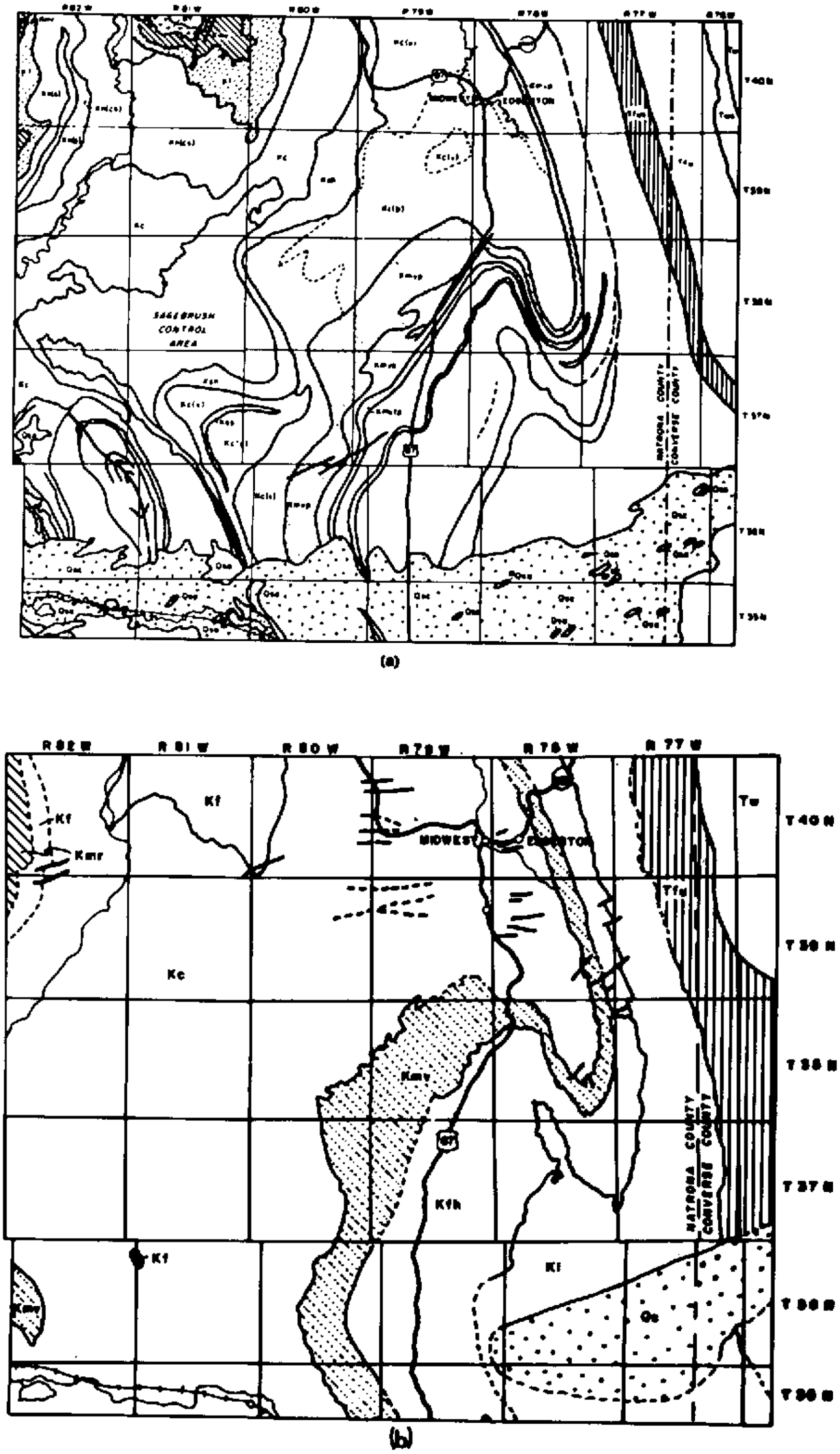

Figure 4. Details of the southeast 1/4th of the map of the Arminto area in central Wyoming as prepared from ERTS imagery (top) compared with the equivalent area taken from the state geologic map (bottom) published in 1955 (courtesy R. S. Houston, University of Wyoming).

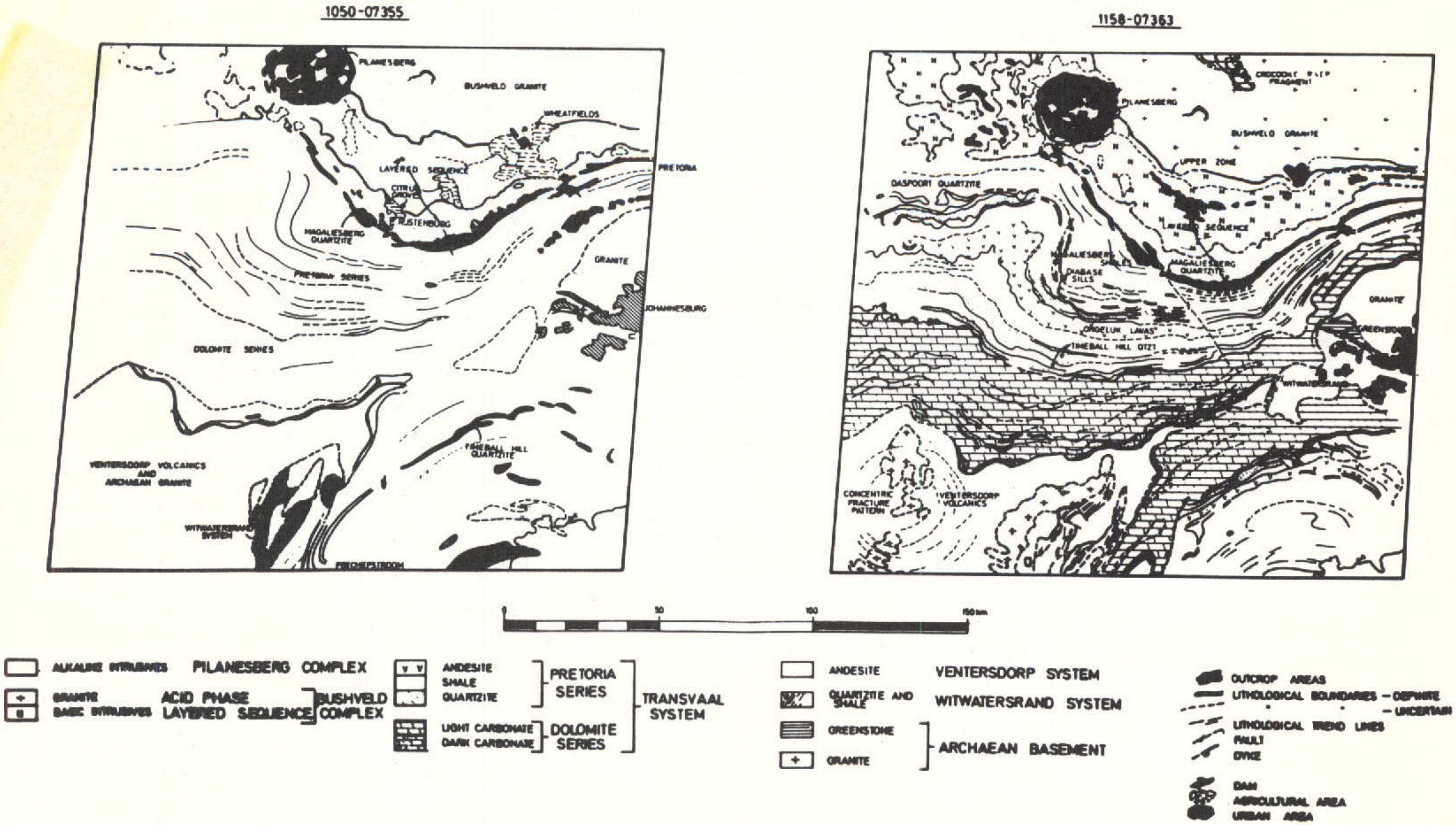

Figure 5. Sketch maps of geologic interpretations made from ERTS images of part of South Africa west of Johannesburg acquired in early September, 1972 during the dry season (left) and late December, 1972 during the wet season (right).

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Figure 6a. ERTS red band image of a region in western Australia just south of the northwest coast near Port Hedlund showing several large igneous plutons cutting into metamorphic rocks (mantling bands).

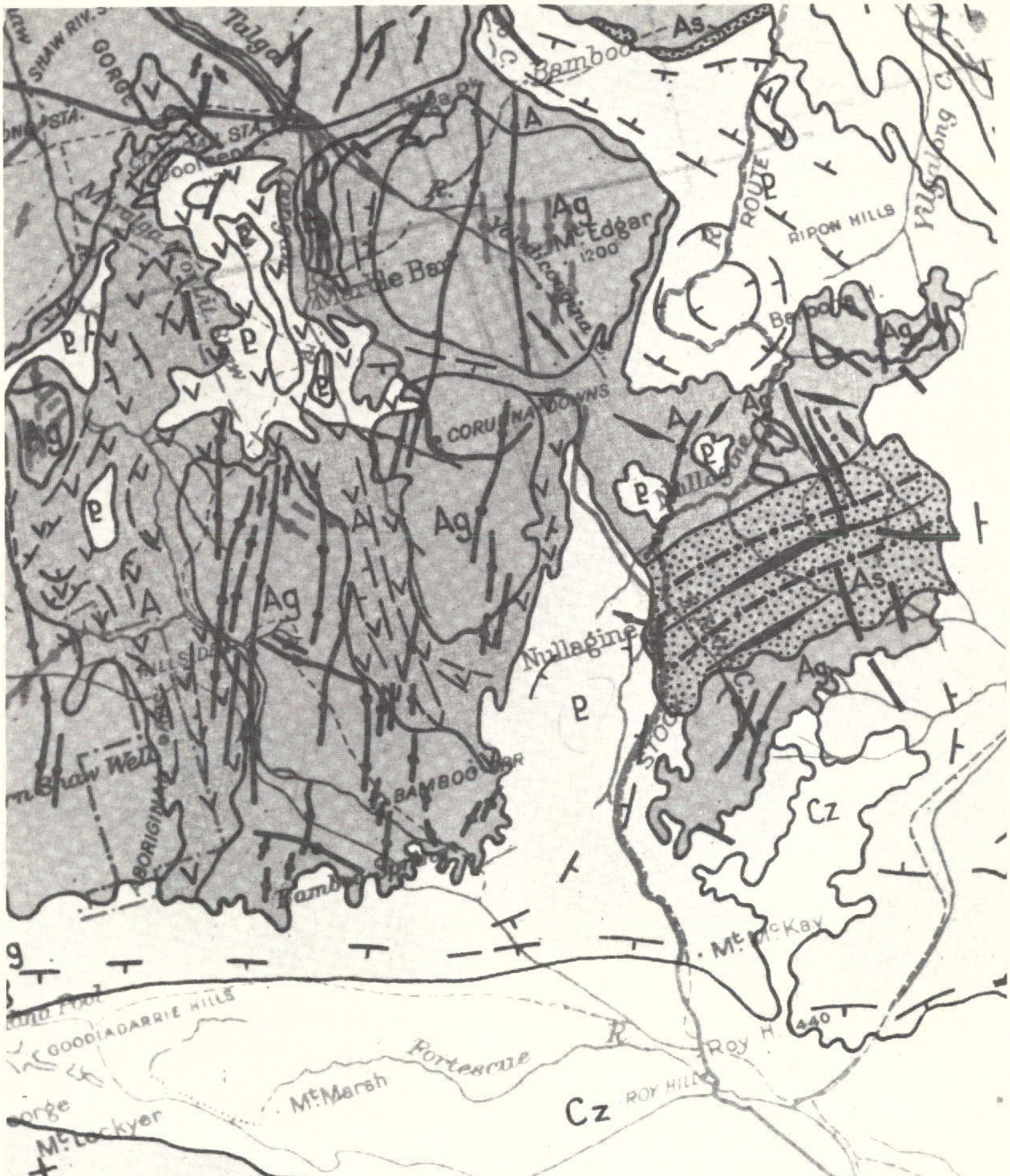

Figure 6b. Part of the Tectonic Map of Australia that includes almost all of the area imaged in Figure 6a. Ag, As, and A refer to Archean granitic and metamorphic rocks; P denotes Proterozoic metasediments; Cz relates to Cenozoic sediments. Close comparison between mapped unit boundaries here and those in the ERTS image reveals that improvements in the precise locations of these boundaries can be made from the ERTS view.

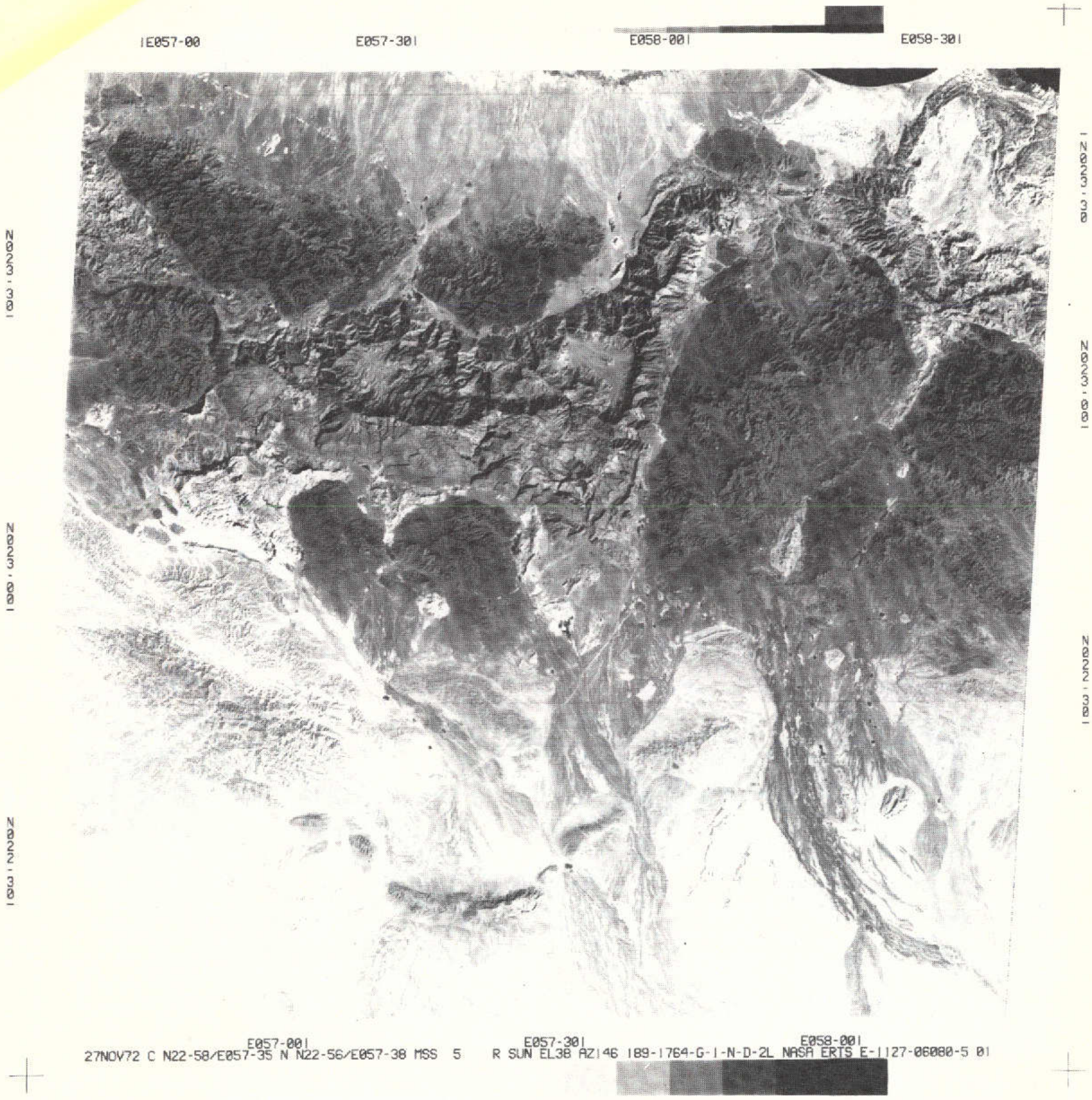

Figure 7. The Oman Mountains in Oman along the Gulf of Oman in the northeast sector of the Arabian Peninsula. The darker areas are mostly ophiolites and serpentines. Several folded belts of Paleozoic and Mesozoic carbonate-shale sequences lie between the basic igneous intrusives; one near top center has been breached to exposed Paleozoic dolomites. Tightly folded radiolarites and other sedimentary rocks are evident in center left.

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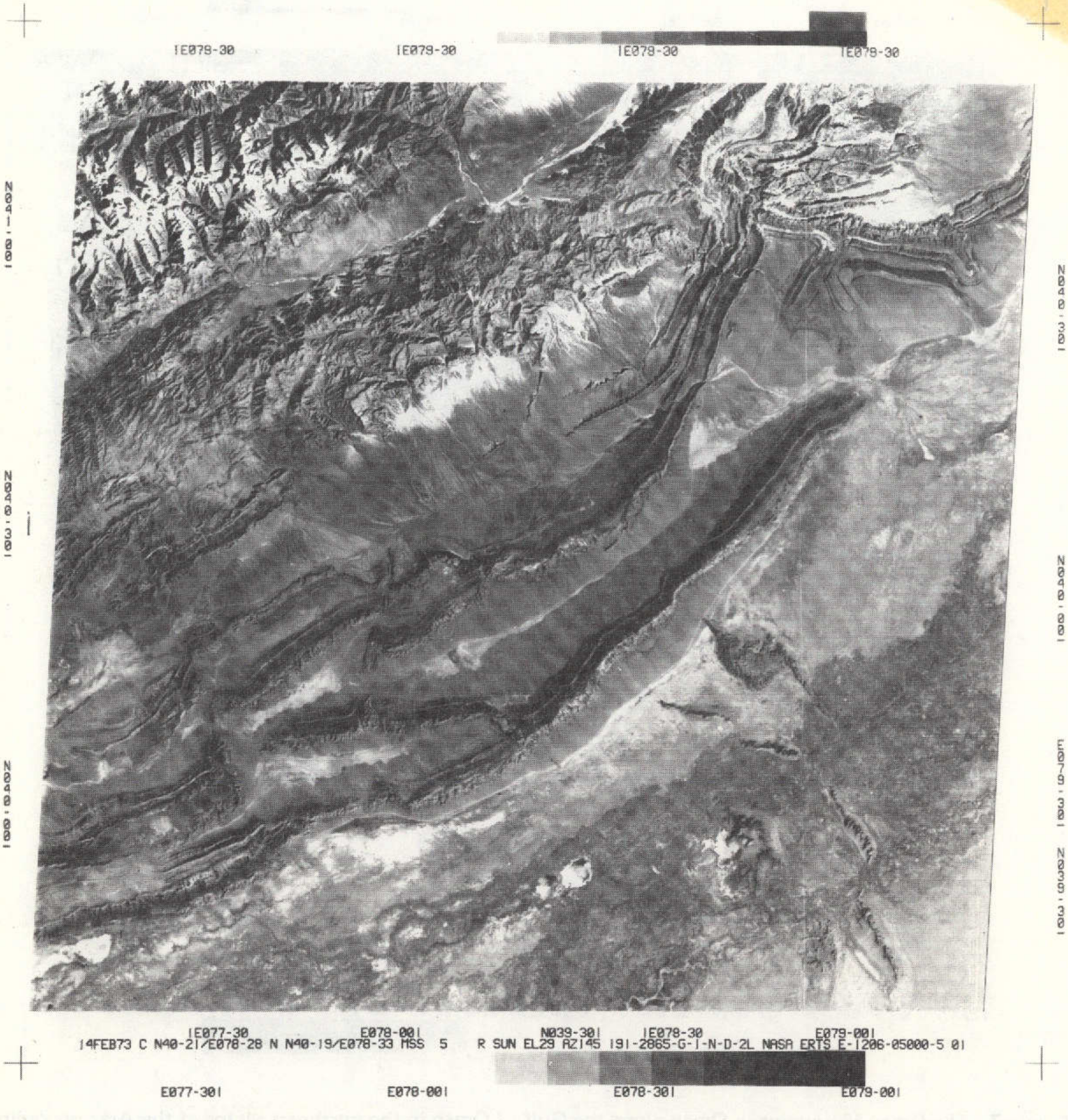

Figure 8a. Broad folds, offset by faults, of the K'op'ing Shan, a series of ranges set against the edge of the Takla Makan desert of western Sinkiang Province in westernmost China. The higher mountains to the north are part of the Tien Shan which passes along the border with the Kirgiz Republic in the USSR

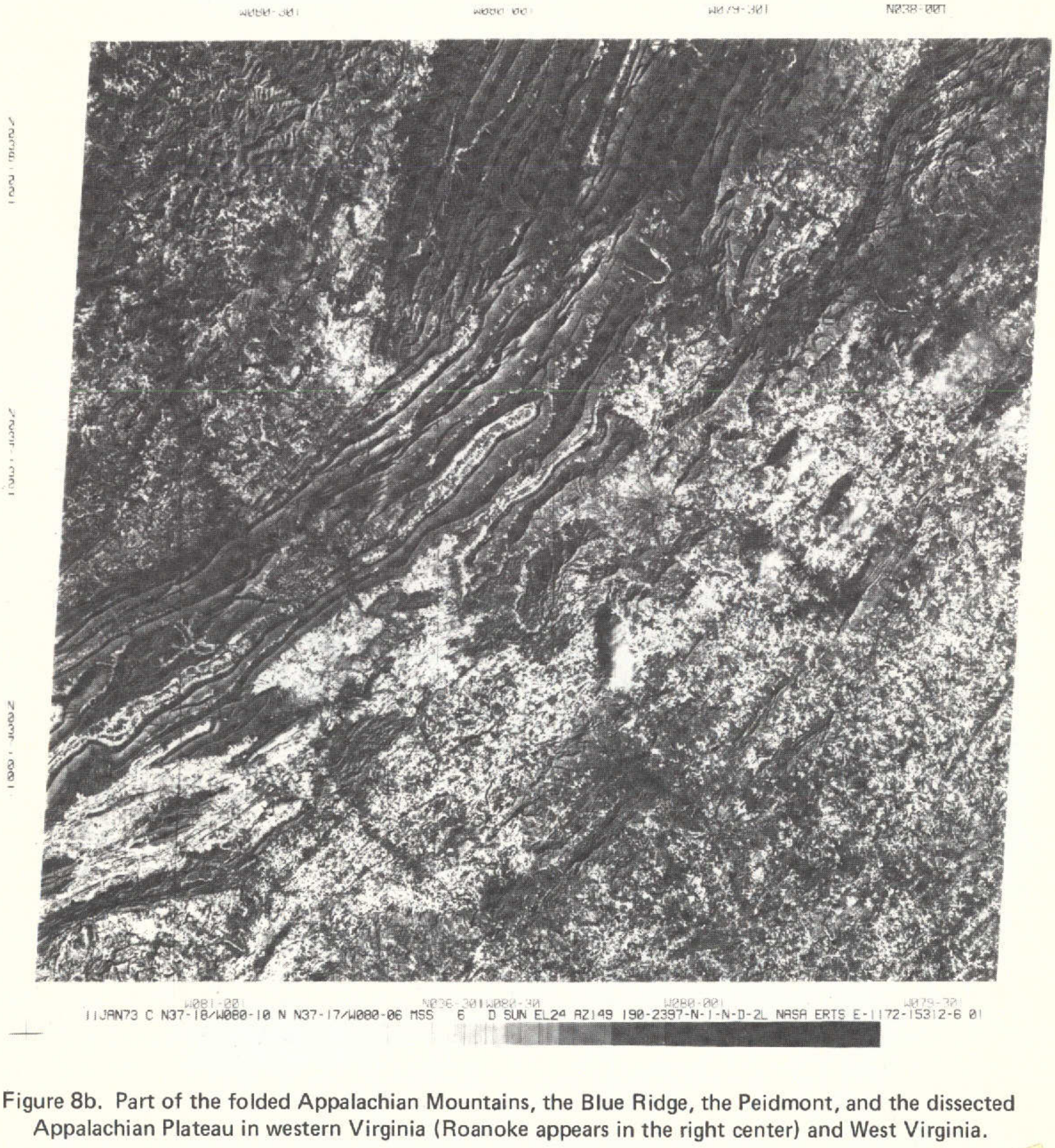

Figure 8b. Part of the folded Appalachian Mountains, the Blue Ridge, the Peidmont, and the dissected Appalachian Plateau in western Virginia (Roanoke appears in the right center) and West Virginia.

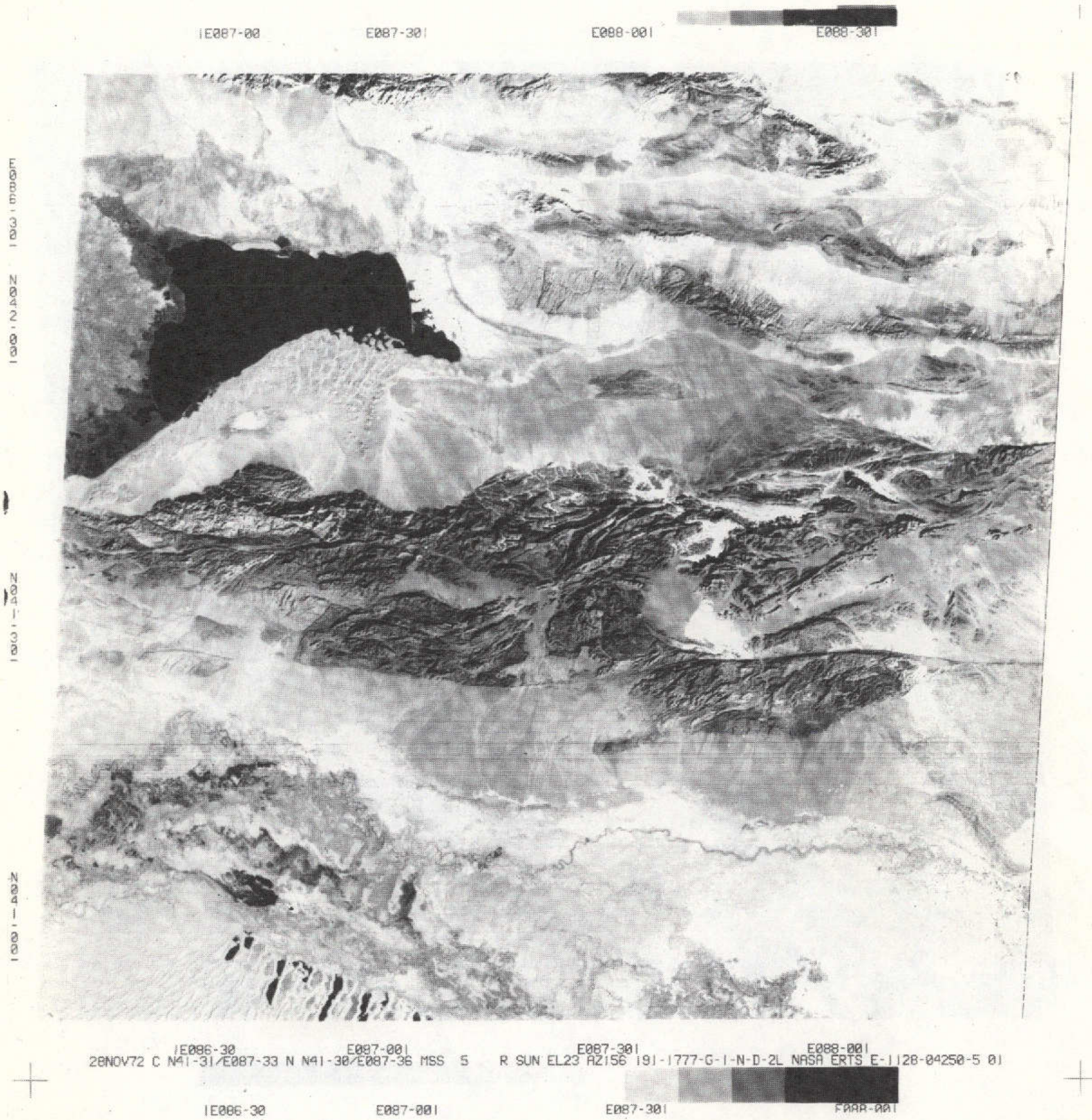

Figure 8c. The Kuruk Tagh mountain range, a complex of Precambrian igneous and metamorphic rocks and infolded Ordovician rocks in the Sinkiang Province of China. The great east-west wrench or tear fault can be traced for more than 300 miles. Lake Baghrash lies to the north.

Figure 8d. A band 7 (IR) ERTS image of the eastern end of the Great Slave Lake in Canada's Northwest Territories. Glacially-scoured fractures in the Precambrian crystalline rocks and glacial lakes in moraines are filled with water in this scene; the water appears very dark in this infrared and thus tends to delineate these structural and geomorphic features.

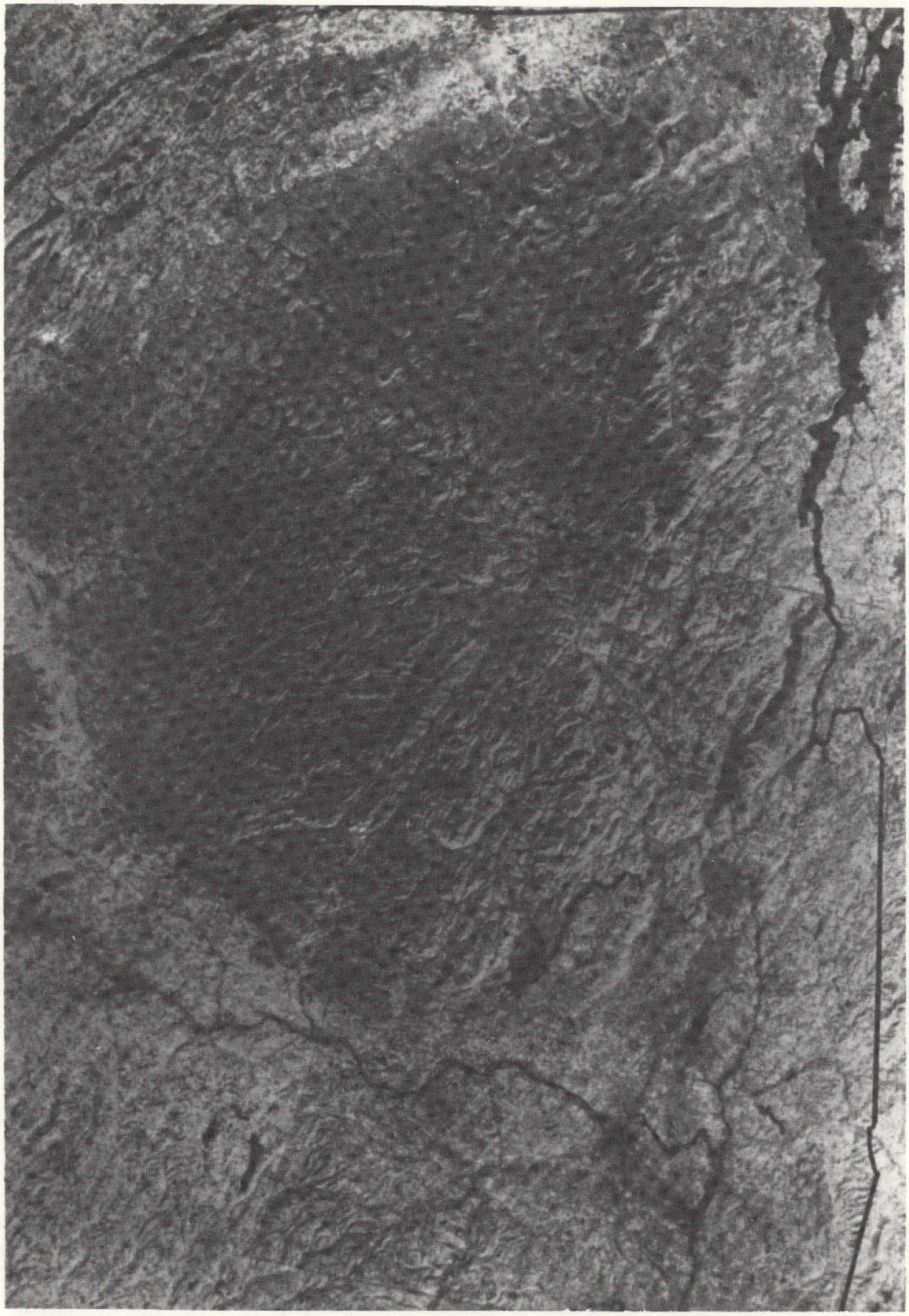

Figure 9. ERTS mosaic showing the entire Adirondack Mountains of Eastern New York. The St. Lawrence River appears at the upper left, Lake Champlain at the upper right, and the Mohawk River near the bottom (courtesy Y. W. Isachsen).

Figure 10. Sketch map of previously mapped lineaments (solid lines) and new "linears" (dotted lines) not all of which have proved to be rock fractures, observed in ERTS images of eastern New York (courtesy Y. W. Isachsen).

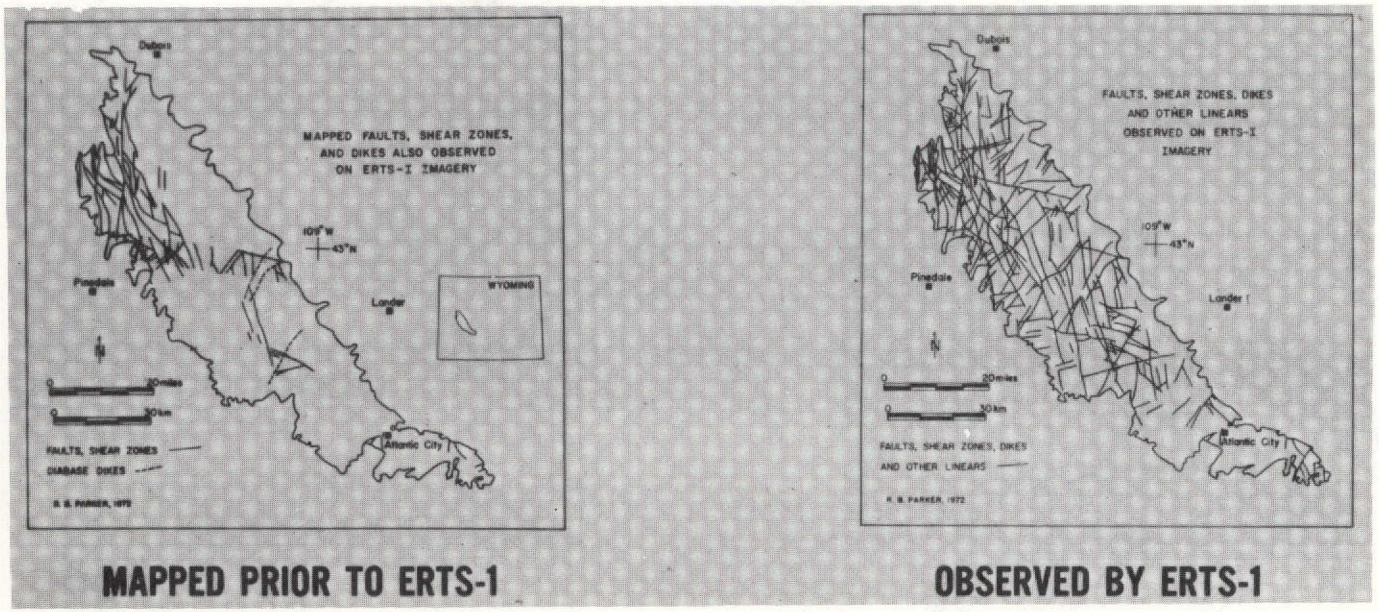

Figure 11. Interpretation of major fracture systems in the Wind River Mountains of western Wyoming made by R. B. Parker of the University of Wyoming from field studies prior to 1972 (left) and then updated by analysis of a single ERTS image (right).

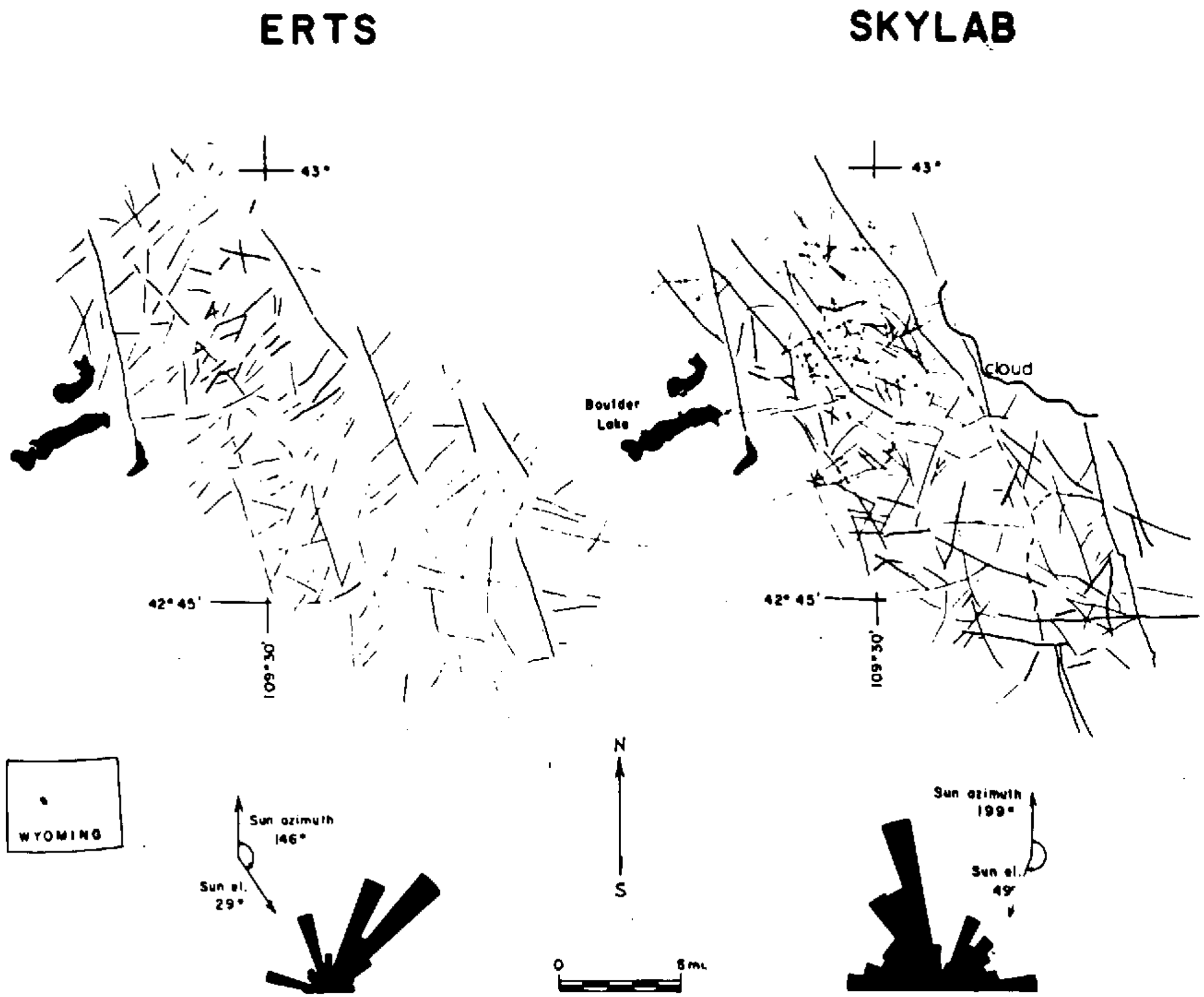

Figure 12. Comparison of linear features mapped using ERTS images and Skylab S-190B photographs of a part of the Wind River Mountains. The rose diagrams indicate the sun-azimuth bias introduced by acquiring the images in the morning and the photographs in the afternoon (courtesy R. S. Houston, University of Wyoming).

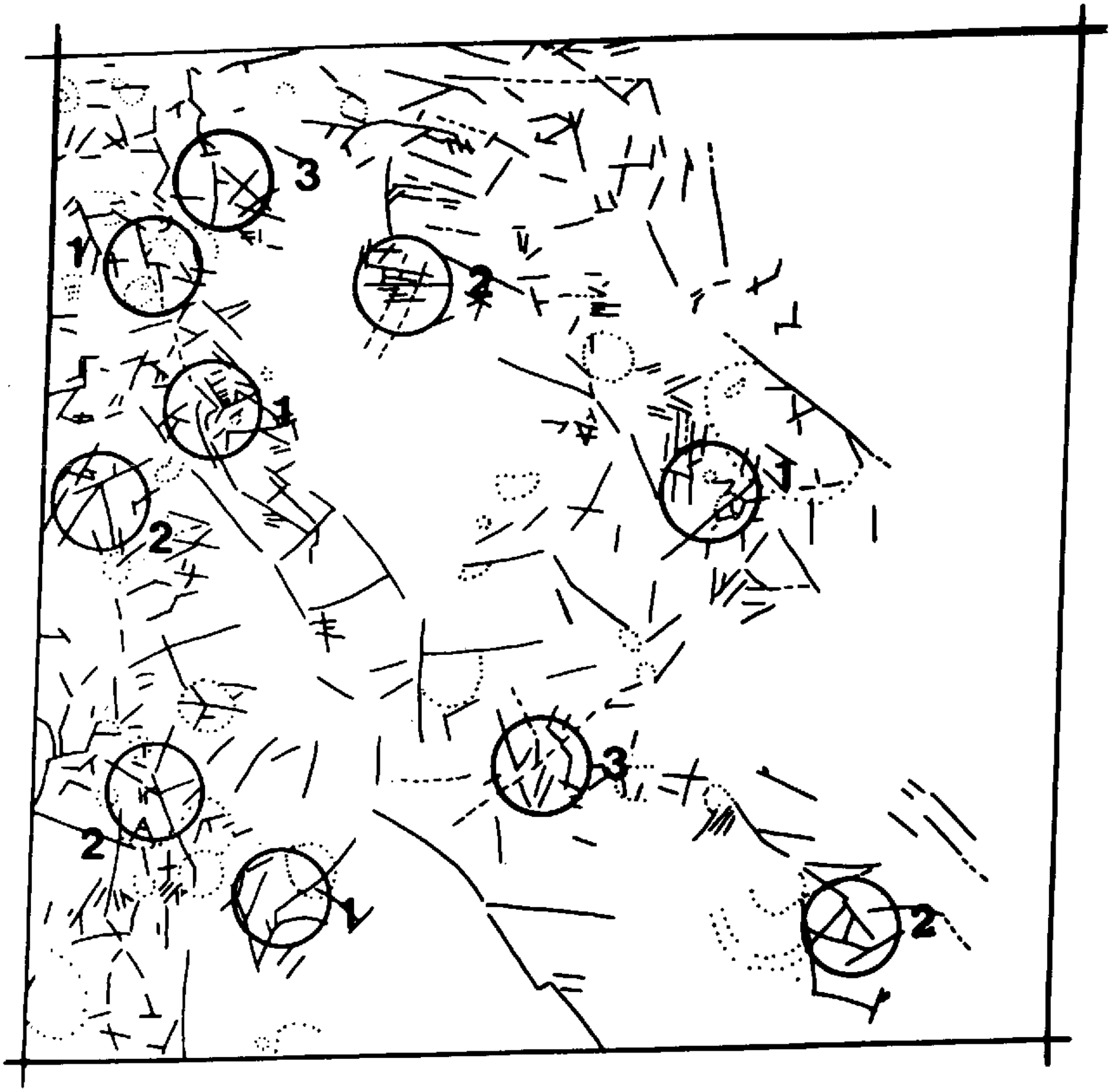

Figure 13. Tracing of straight and curved or arcuate linear features recognized in ERTS imagery on a winter ERTS scene over the Central Mineralized district of Colorado. The area is south of Denver; Colorado Springs appears in the right center. Higher frequencies (or densities) of linears have been circumscribed (from S. Nicolais, 1973).

Figure 14. ERTS Band 5 mosaic of much of the southwestern United States, including central and southern California, southern Nevada, and small parts of Arizona; northern Mexico around the mouth of the Colorado River is also shown. This is part of the mosaic of the United States prepared by the Soil Conservation Service.

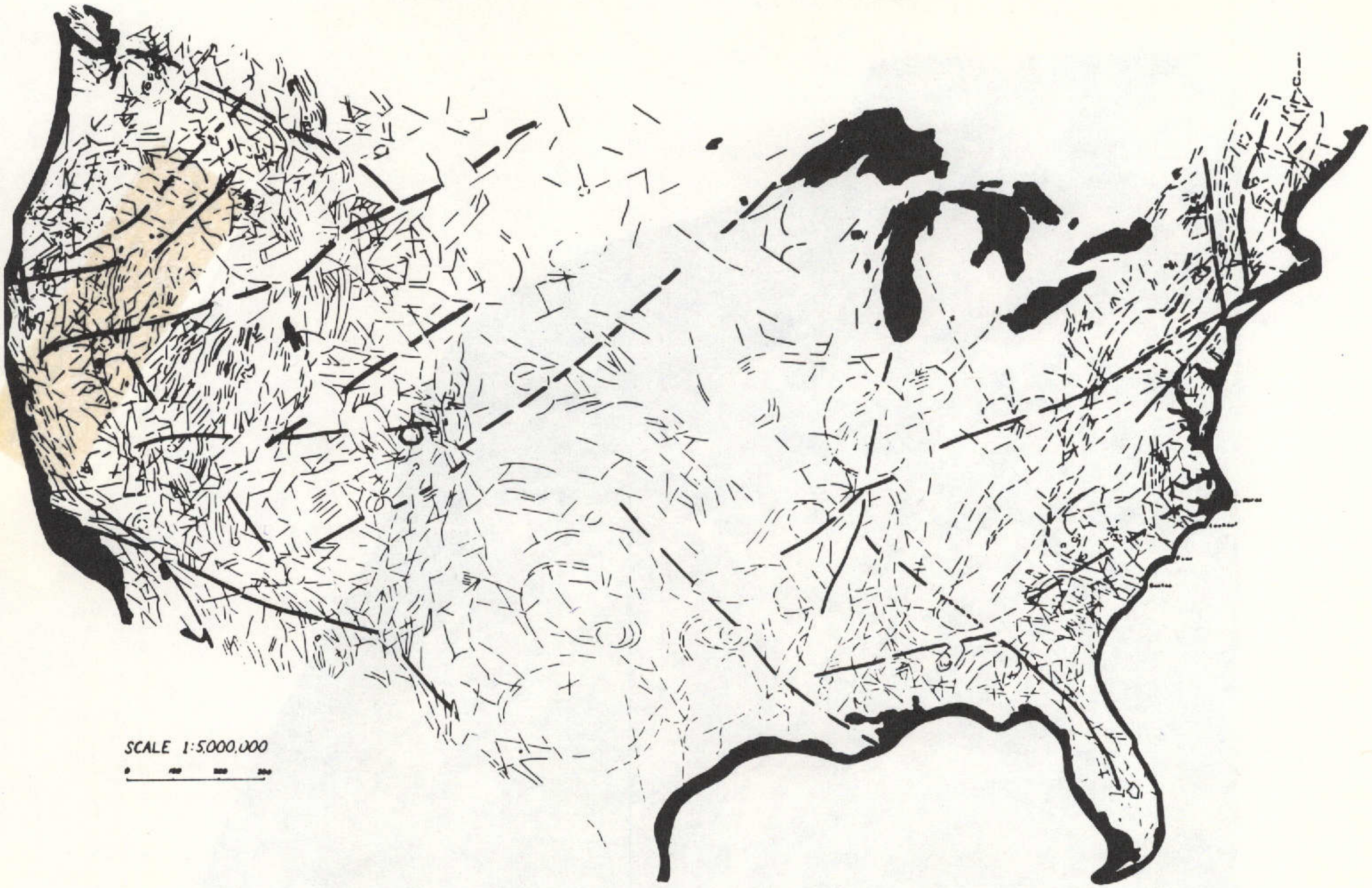

Figure 15. Sketch map outlining the United States on which W. D. Carter of the United States Geological Survey, Reston, Virginia, has plotted the major or regional straight and curved linear features that he could recognize in a preliminary examination of the ERTS mosaic of the entire United States

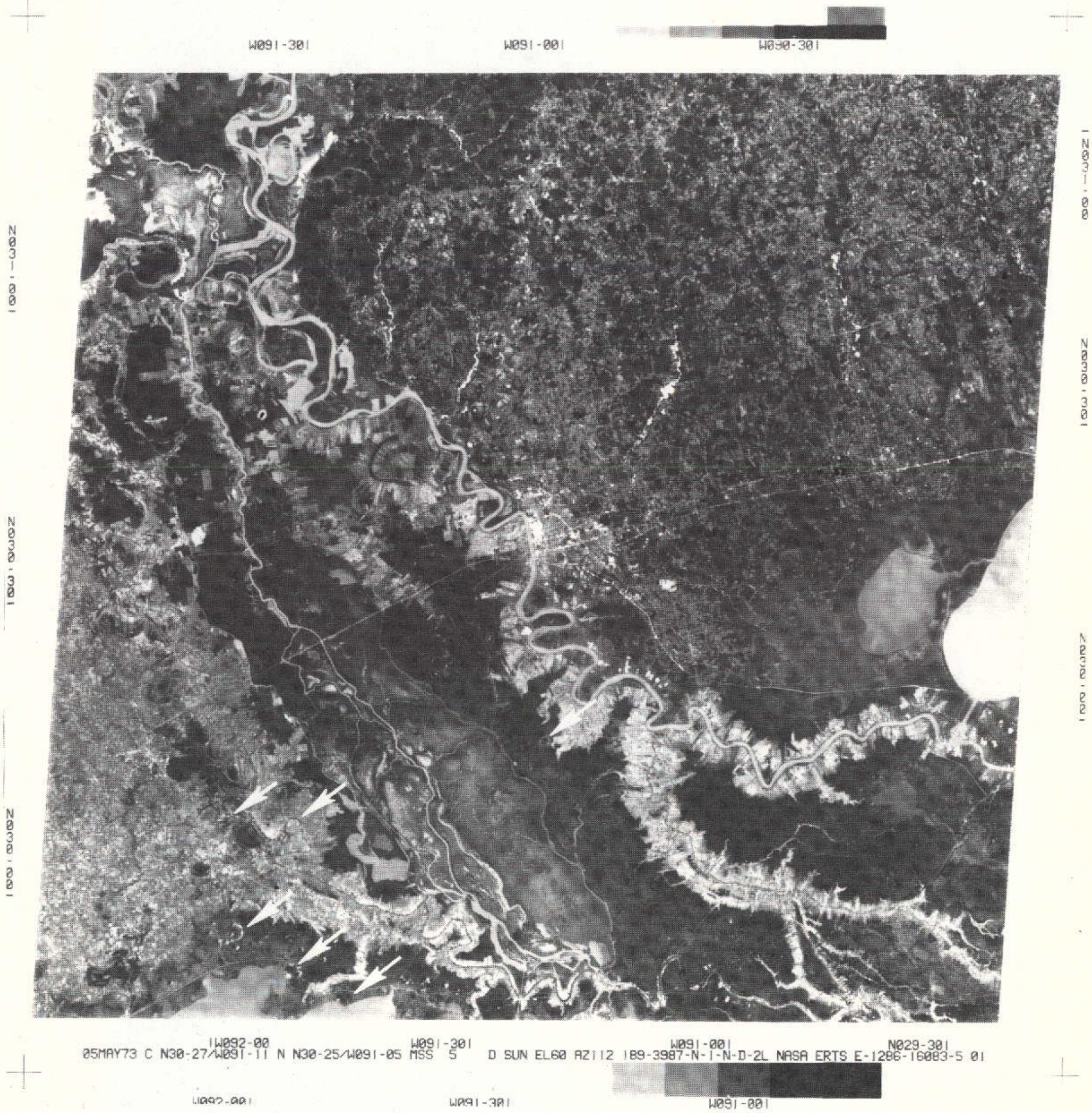

Figure 16. ERTS image of southern Louisiana (just west of New Orleans) and southwest Mississippi (top) through which flows the Mississippi River past Baton Rouge and the Atchafalaya River to the west. Numerous salt domes occur in this region; several which are easily identified in this band 5 image are indicated by arrows.

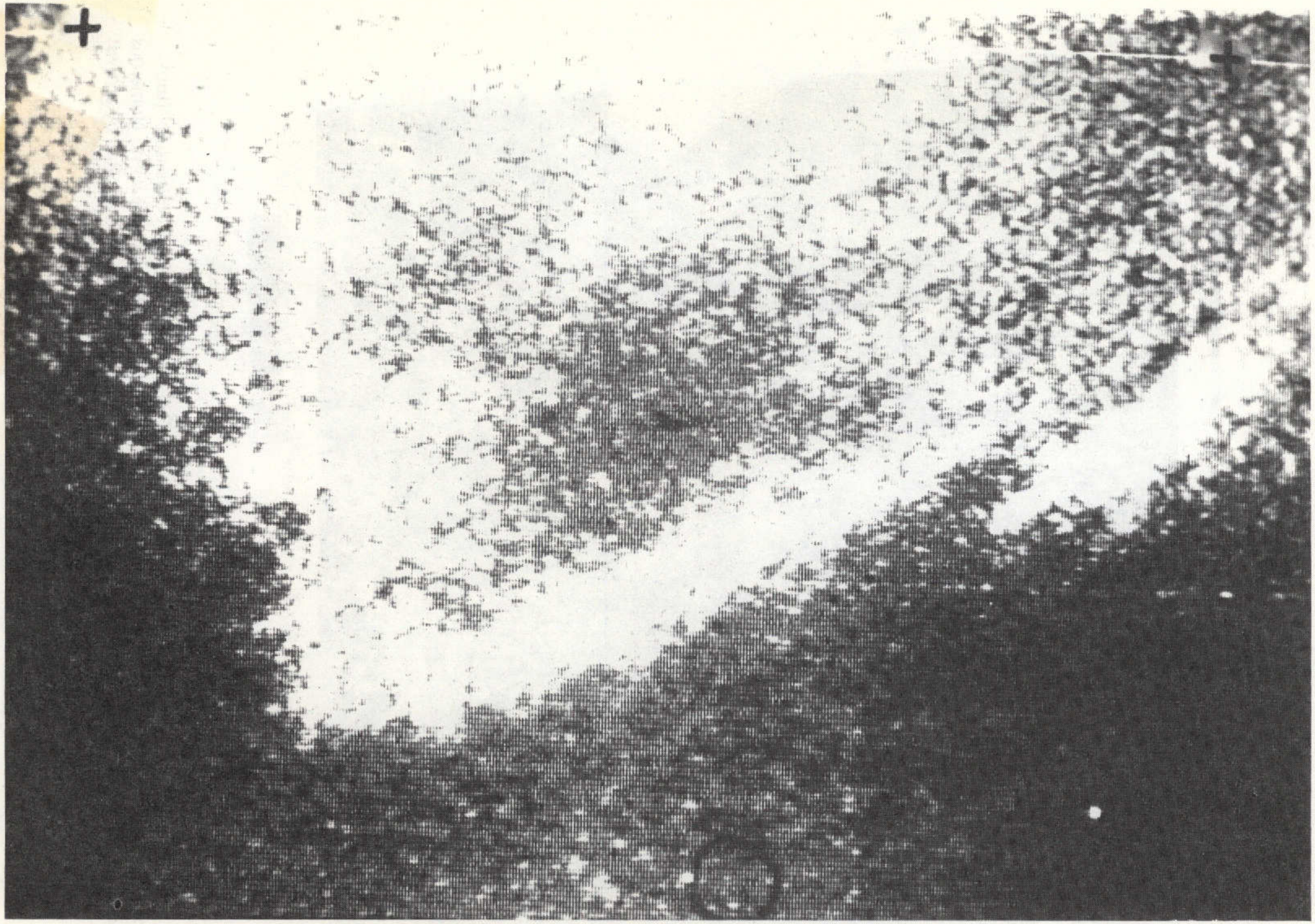

Figure 17. Black and white version of a color-enhanced photograph of the surface "slick" formed from a natural oil seep in the Gulf of Mexico. The photo was made during a NASA aircraft overflight over known seeps to test methods for detection of oil on the sea surface by remote sensing. As shown here, best detection was achieved with a No. 35 filter (near UV-blue) over the KA62 camera loaded with panchromatic film (courtesy J. A. Eyer, Continental Oil Company).

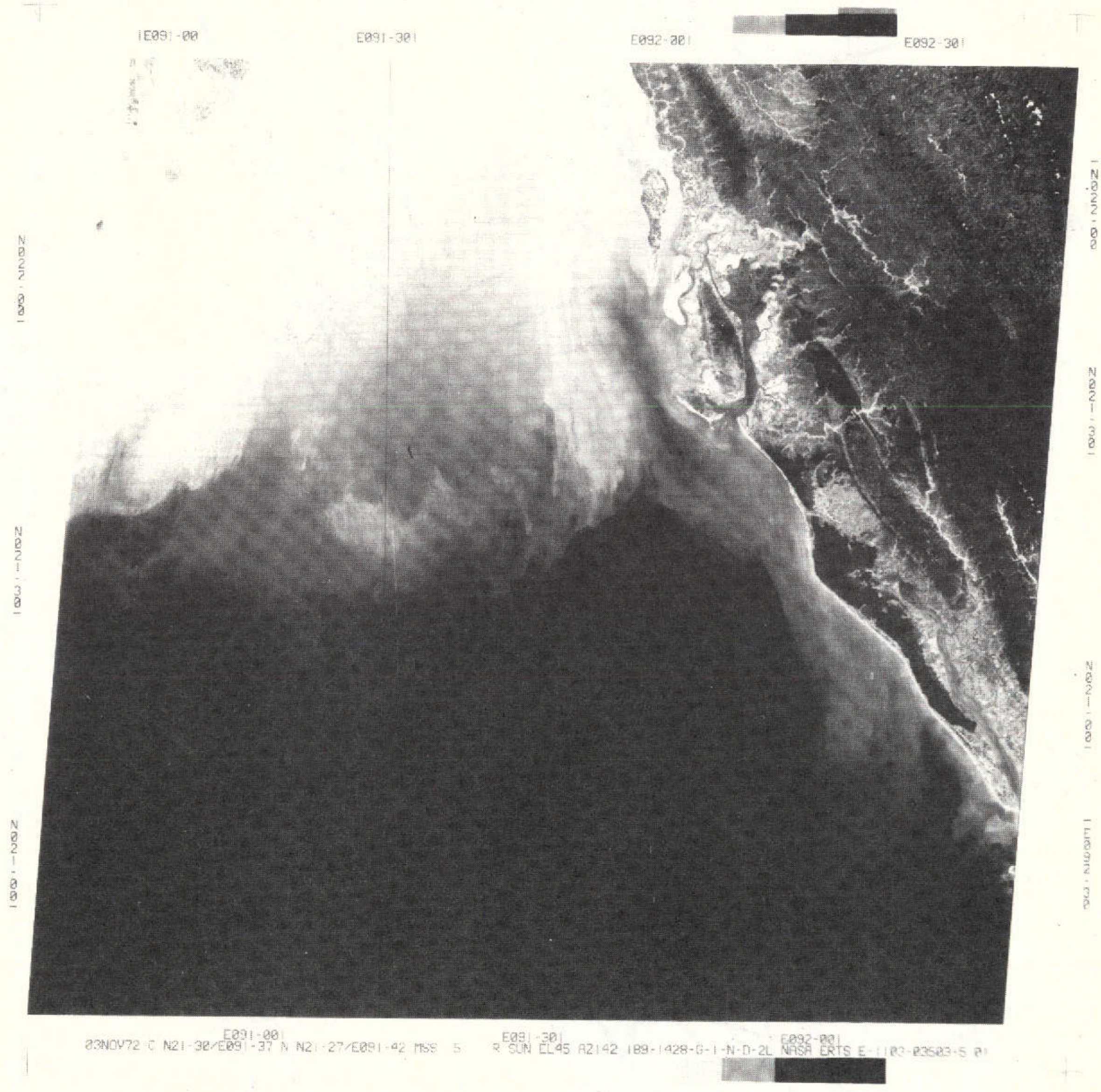

Figure 18. Sedimentation pattern of discharge zone of the Ganges River into the Bay of Bengal south of Bangladesh, ERTS band 5.

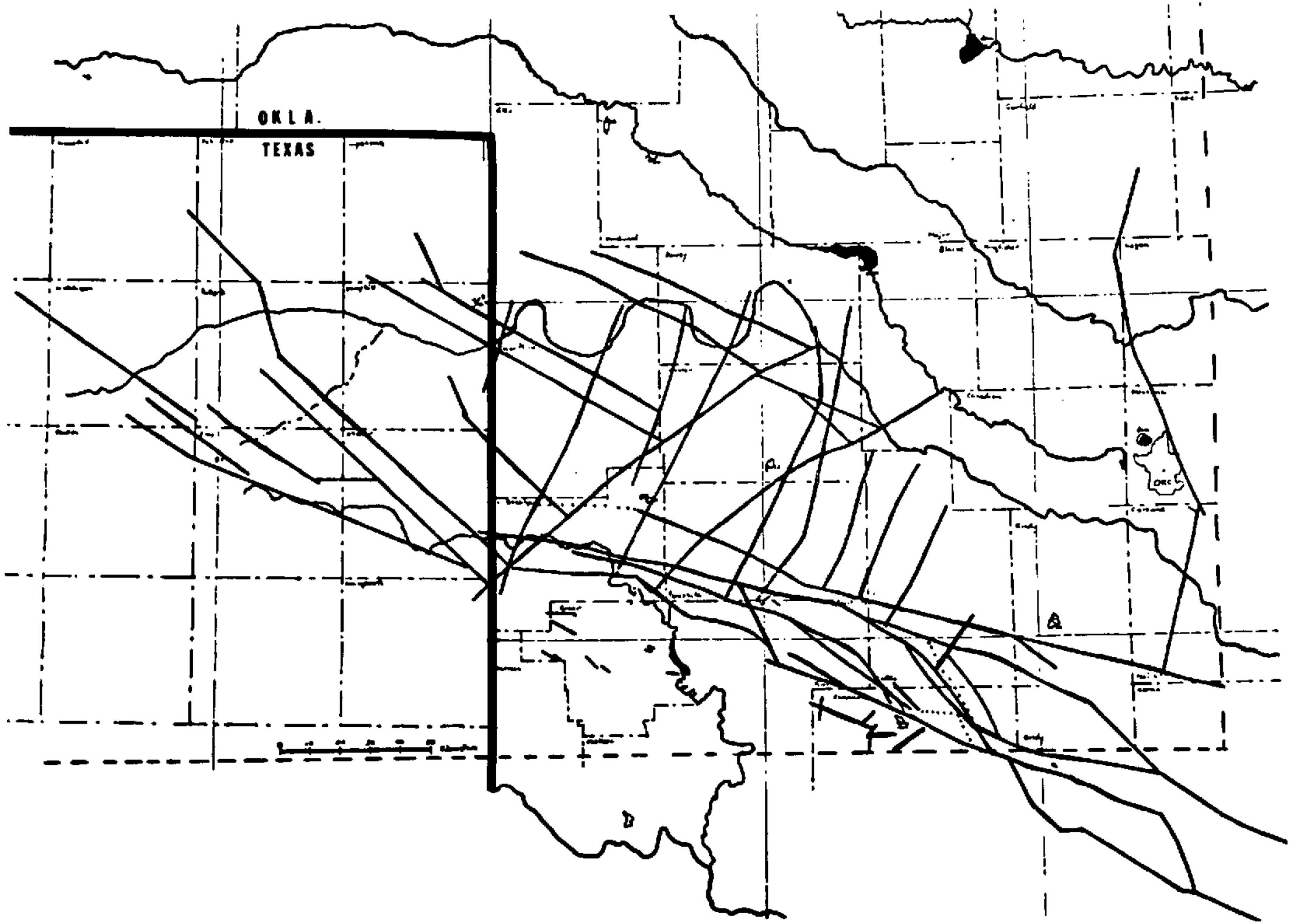

Figure 19a. Tracing on a geographic base map of the major known and hypothesized faults and linears expressed at the surface over the Anadarko Basin (from Eason Oil Company final ERTS report).

Figure 19b. Linears recognized in ERTS imagery covering the Anadarko Basin and surrounding areas in Oklahoma and Texas. Heavy lines emphasize ERTS linears coincident with or extending from linear features plotted in Figure 19a.

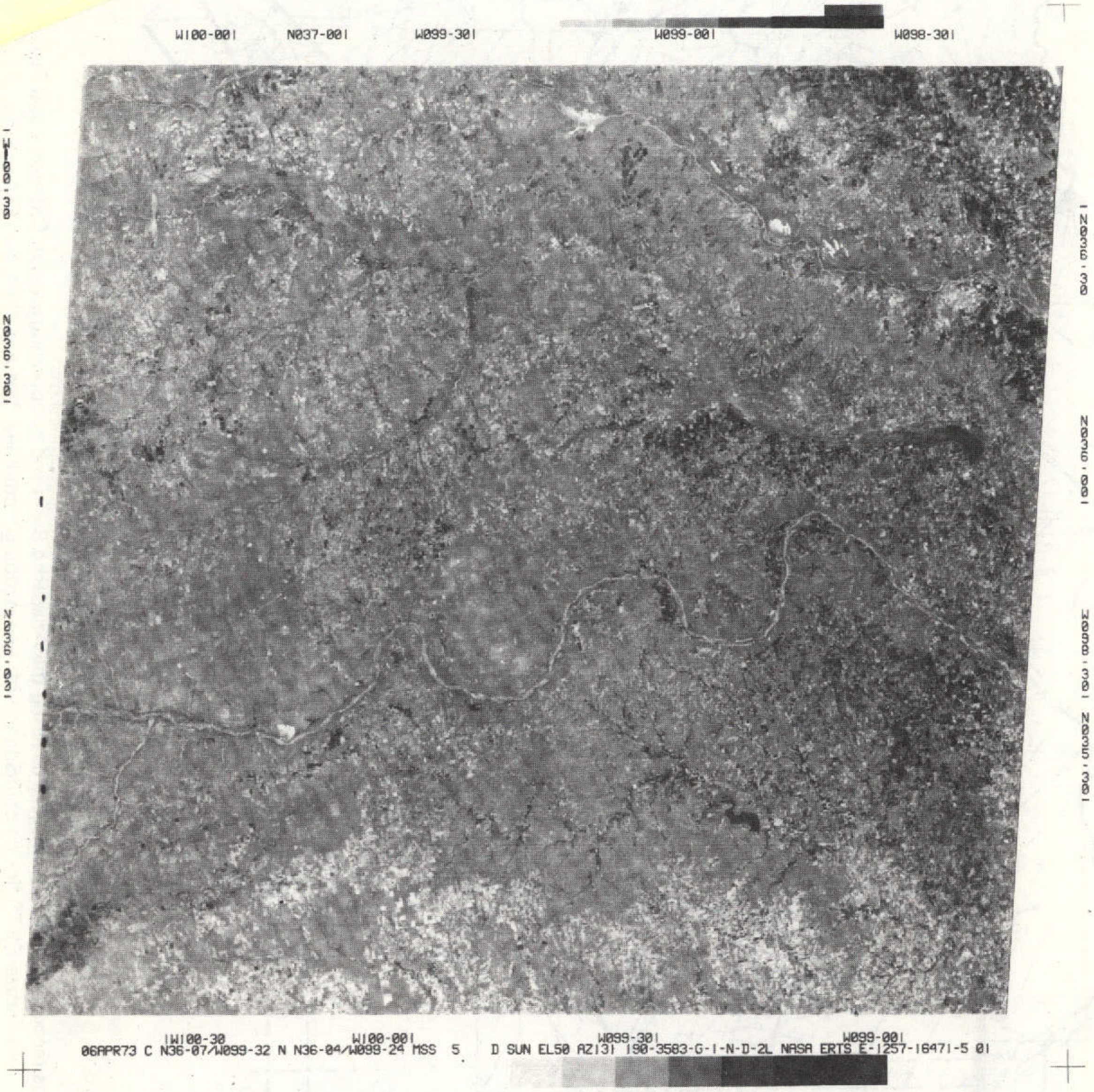

Figure 20. ERTS band 5 image covering part of western Oklahoma and some of the Texas panhandle. The meandering Canadian River and the North Canadian River are the principle drainage features. "Hazy" anomalies are particularly evident in the bend of the Canadian River near the center of the image.

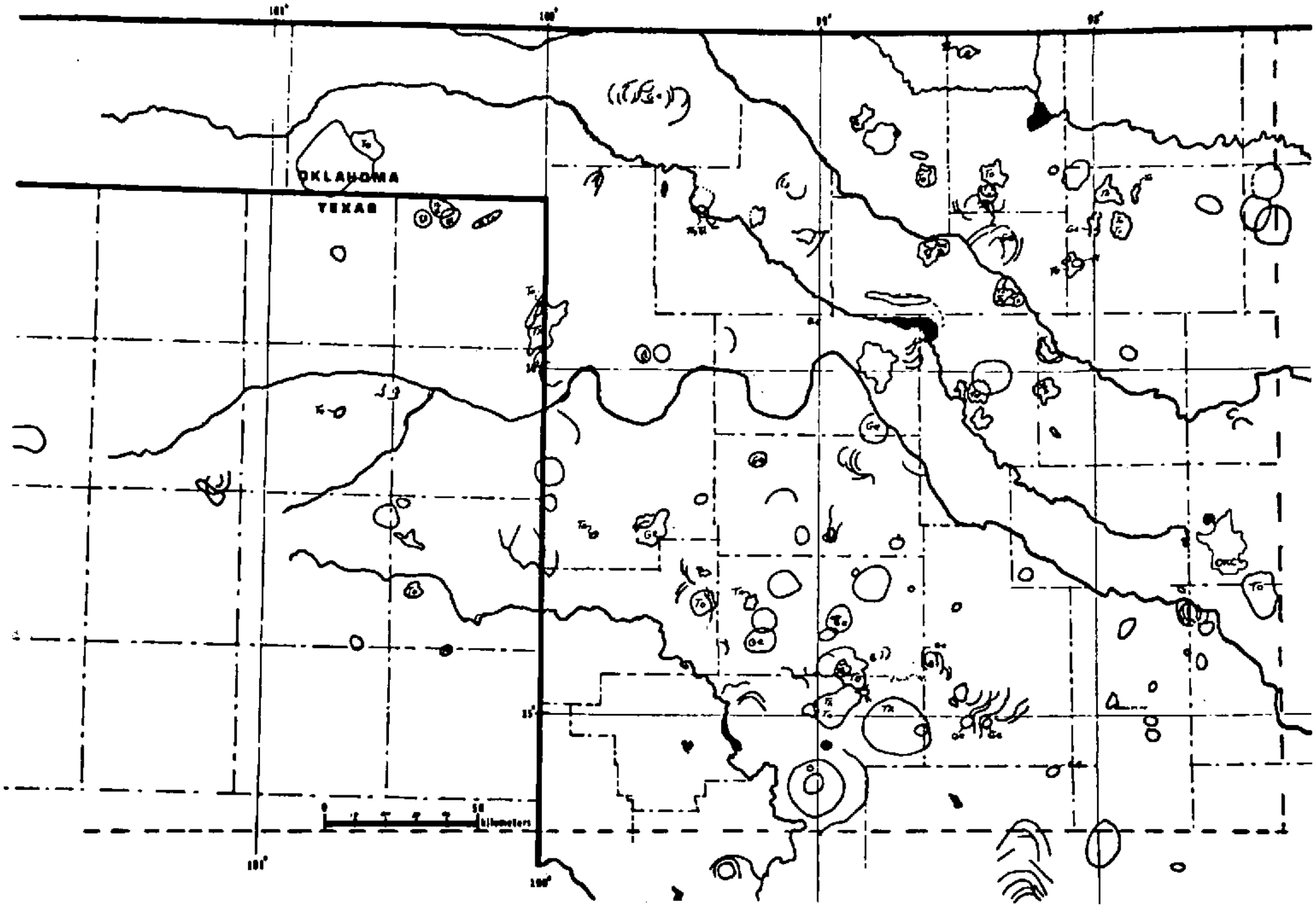

Figure 21. Sketch map showing the traced outlines of many of the closed anomalies recognized in the Anadarko Basin during the Eason Oil Company ERTS investigation. To refers to tonal anomalies, Tx to textural anomalies, and Ge to geomorphic anomalies (from Eason Oil Company final ERTS report).

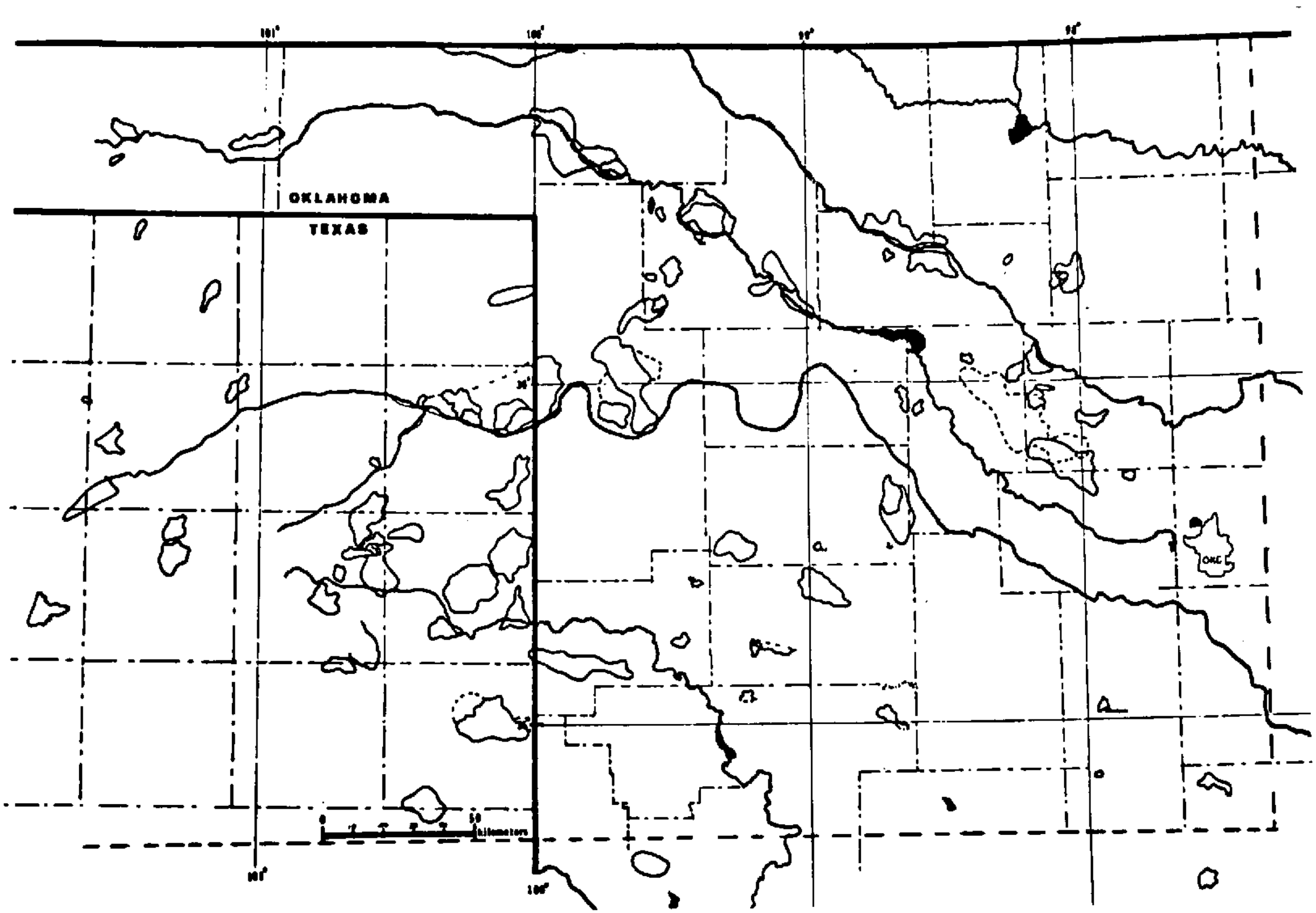

Figure 22. Sketch map of hazy anomalies in the Anadarko Basin study area (from Eason Oil Company final ERTS report).

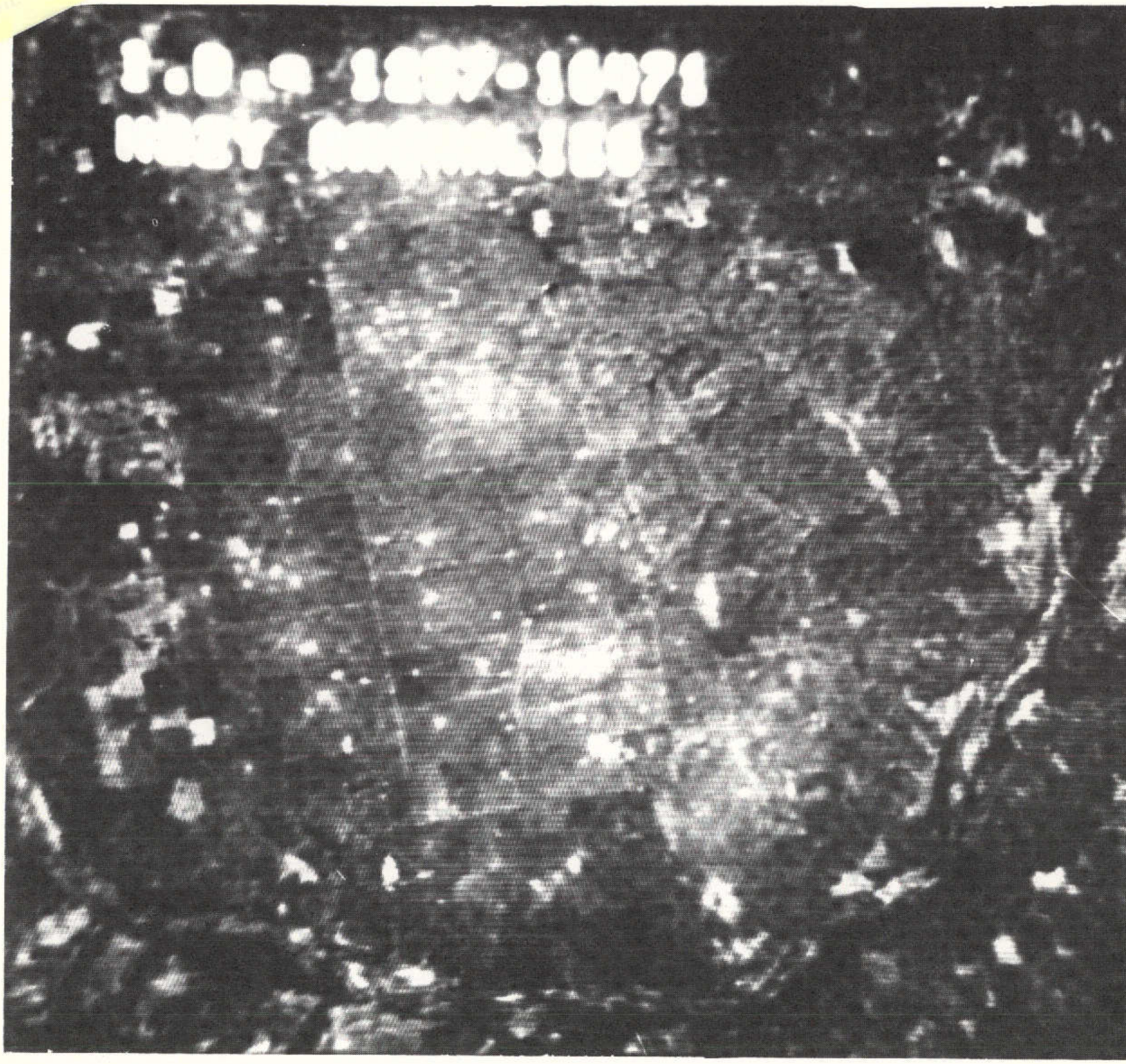

Figure 23. Black and white version of color image photographed from the TV monitor screen of the Image 100 computer-interactive processing system at the General Electric Space Sciences Laboratory in Beltsville, Maryland. This scene shows a bend of the Canadian River in western Oklahoma enlarged to a scale of approximately 1:30,000 from the original scale of the same ERTS image shown in Figure 20; however, this rendition is made entirely from the ERTS computer-compatible tape of the April 6, 1973 pass over Oklahoma.

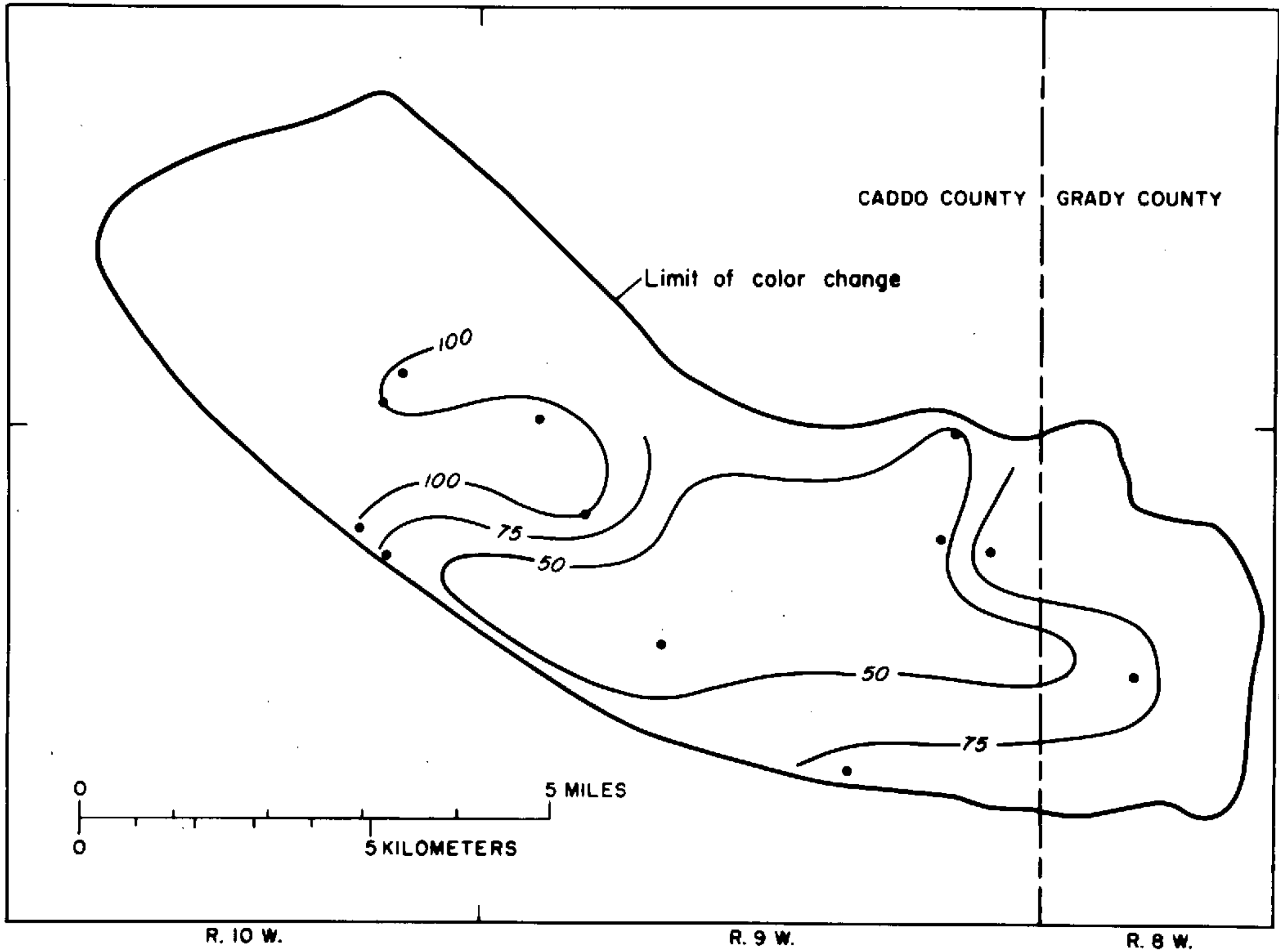

Figure 24. Contoured values of total iron content (in parts per million; each number should be multiplied by 100) within the "bleached" areas of the Rush Springs sandstone (Permian) exposed at the surface over the Cement field, Anadarko Basin, Oklahoma. Solid dots represent sample locations (courtesy T. J. Donovan, U. S. Geological Survey).

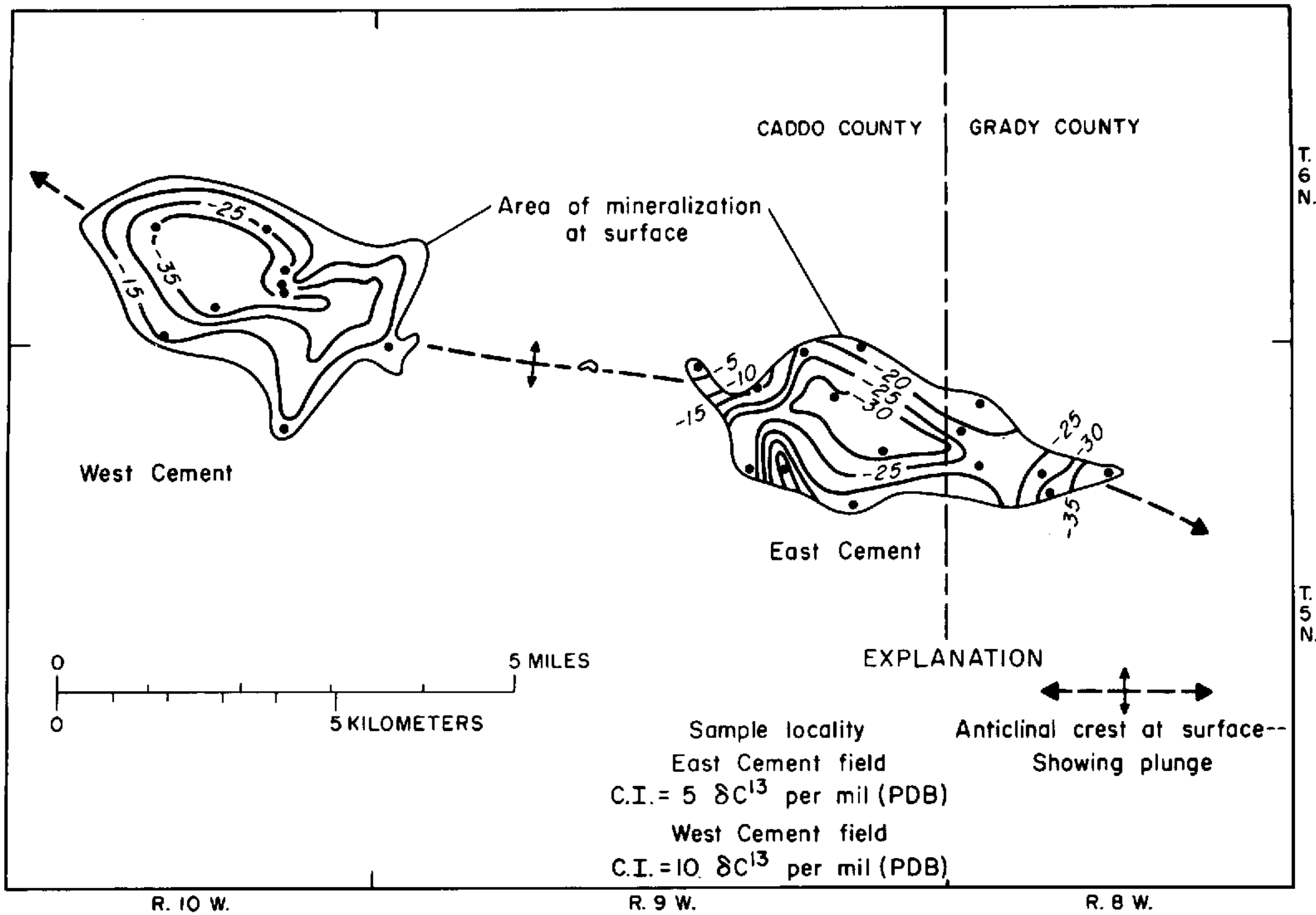

Figure 25a. Variations in carbon-isotope composition within the area of strong carbonate mineralization of the Rush Springs sandstone at the Cement field (courtesy T. J. Donovan, U. S. Geological Survey).

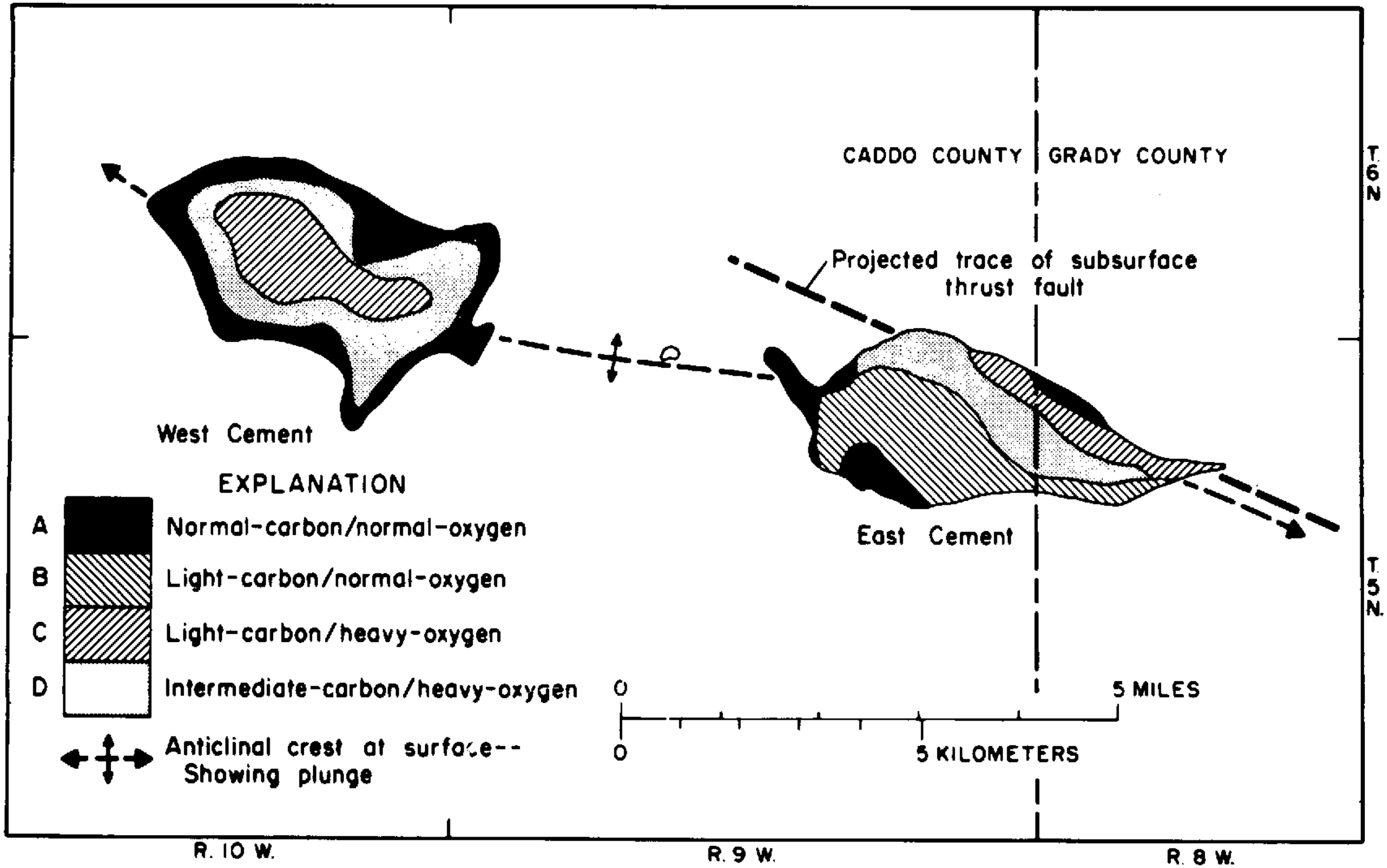

Figure 25b. Distribution of different types of carbonate cement in the Rush Springs sandstone based on the relative proportions of different carbon and oxygen isotopes (courtesy T. J. Donovan, U. S. Geological Survey).